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TO OPEN - *twist bottom levers clockwise slightly as you press them.*

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SPECIAL WARNING

This Handbook has been prepared for use in the Establishments of the U.K.A.E.A. Criticality is a subject of particular complexity and the information given herein assumes special knowledge of it. Danger could arise if the data given in the following pages were to be used by someone not fully conversant with criticality. The Authority therefore cannot accept responsibility for any injury or damage which might result from any of the recommendations contained in this Handbook being followed in premises not under the Authority's control.

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"My son, these maxims make a rule,
Dinna lump them ay thegither;"
(with apologies to the "Unco Guid")

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FOREWORD

The data presented in this Handbook have been considered and approved by an Editorial Committee representing the General Neutronics Section of Central Technical Services (Development and Engineering Group) and the Criticality Inspectorate of the Authority Health and Safety Branch.

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The committee wish to acknowledge the help of the following in provision of data for the handbook:

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They also wish to thank Mr T. Brown of C.T.S. and Mr G. Walker of A.H.S.B. for drawing curves.

SECTION A: Introductory notes

1. Collections of criticality data have been available for some time.[1, 2] In general, these sources have included data which are either stated to be "safe" or have given critical parameters for "limited density" materials such as diffusion plant products. Where "safe" figures have been quoted, little indication of the safety factors involved has been given. This has frequently led to doubt as to the margin of safety implied. It is considered that by presenting critical parameters a more confident assessment of safety can be made.

In this Handbook are presented only agreed critical parameters and these are given for the most reactive systems considered likely to arise in processing plants. The most reactive systems will be clearly defined in each of the sections into which this Handbook is divided. It is not intended to give theoretical justification of the data, but reference will be made to the original reports from which the data have been taken. Any queries concerning the data, or any suggestions for extensions or revisions, should be made to the Secretary of the Editorial Committee.

There are certain assumptions and definitions upon which any simple presentation of criticality data must be based. Since the data presented are intended for use by chemical plant designers and operators, these assumptions and definitions are based on operations and accidents that might reasonably be considered possible in such plants.

2. ASSUMPTIONS AND DEFINITIONS

(1) The most dangerous type of neutron moderating material that can arise deliberately or accidentally in most chemical processes is hydrogenous. For most practical purposes this means water or oil, but other hydrogenous compounds must be considered. Specifically excluded from this category of moderators are such materials as beryllium, beryllium oxide, heavy water, and graphite. These materials are potentially better moderators than water and are treated separately.

(2) With this restriction on moderators in sections B to F the degree of moderation is expressed as the ratio of the number of hydrogen atoms to that of fissile isotope atoms in the mixture (known as the H/X atomic ratio, where X may be ^{235}U or ^{239}Pu). The most reactive homogeneous form of fissile material and moderator is that in which the fissile isotope concentration* is greatest for a given H/X atomic ratio. The data on homogeneous mixtures or solutions are based on metal-water systems. Any crystal form exhibiting a lower concentration of fissile material than metal will form a less reactive system for a given H/X atomic ratio.

One chemical form of fissile material which must be considered separately is the hydride. A hydride can give significant H/X atomic ratios with exceptionally high fissile isotope concentrations, and is therefore a potentially more dangerous material than any considered in sections B to F.

For uranium systems with ^{235}U enrichments of 5% or less, the effect of heterogeneity is important. It is known that lattices of uranium metal rods or lumps interspersed with water can yield

*'Concentration' is used throughout this Handbook to mean mass per unit volume, not fissile isotope enrichment

smaller critical masses and dimensions than homogeneous uranium-water mixtures.[3] Consequently, critical parameters for this enrichment range are specified with more detailed regard to physical form and density of the uranium compounds. For ^{235}U enrichments below 5%, the lattice system has a lower minimum critical mass than the homogeneous system. The minimum dimensional parameters of lattice assemblies remain lower than those of homogeneous systems even at appreciably higher enrichments. There are no experimental checks of this effect at enrichments greater than 5%. To cover this effect the safety factors to be applied to the critical parameters for homogeneous systems are increased except in the case of the critical mass.

(3) Random heterogeneities in fissile isotope distribution do not increase the reactivity of the system. Certain heterogeneities[4,5] may give rise to critical masses smaller than those for homogeneous systems, by a few percent, but normal safety margins will considerably exceed maximum credible effects of this kind.

(4) The most dangerous form of reflecting material usually encountered in any process is water. Such materials as human tissue, oil, timber (including artificially pressed forms), concrete, iron, perspex, glass, and similar conventional structural materials, are regarded as being equivalent to water. Reflectors such as beryllium, beryllium oxide, heavy water, natural uranium, and graphite of thickness greater than a nominal 1 in., are treated separately.

(5) All critical parameters given in this Handbook are for fully-reflected conditions. Fully-reflected conditions have been assumed because vessel walls, supports, nearby structural materials, operators, etc. all act as partial or potential neutron reflectors whose effect cannot generally be assessed.

3. PRESENTATION OF DATA

Partly for convenience and partly because the data fall naturally into certain classes, the presentation is made in sections. In each of the sections there are graphs of the four principal minimum critical parameters of mass, volume, diameter of infinite cylinder, and thickness of infinite slab. Comments are included on the reliability of the data and on any special points of interest. In most instances, the data represent a "best" estimate of critical parameter. The data presented in sections B to F is for a single fully-reflected vessel only. The problem of neutron interaction between vessels arising, for example in the storage of fissile material and due to the proximity of plant equipment, is dealt with in section H.

4. HOW TO USE THE HANDBOOK

This Handbook presents graphs of the four commonly encountered critical parameters: critical mass, critical volume, critical radius of an infinite cylinder, and critical thickness of an infinite slab. In the present issue these curves are given in sections B to E for systems involving ^{239}Pu and uranium systems of three ranges of enrichment in ^{235}U, namely 30-93%, 5-30%, and less than 5%. The curves in each section are in the order:

Fig. 1. Critical mass

Fig. 2. Critical volume

Fig. 3. Critical radius of infinite cylinder

Fig. 4. Critical thickness of infinite slab.

For uranium systems the curves at various enrichments are drawn fairly close together so that if a problem of particular enrichment is encountered the use of the nearest curve of higher enrichment should not prove too restrictive.

Having selected the appropriate section of the Handbook and the set of curves relevant to the problem the next important step is to determine the credible range of fissile isotope concentrations and degrees of hydrogen moderation that could occur in the system under consideration. In this assessment any possible abnormal operation of the plant must especially be taken into account (e.g. accidental precipitation or dilution, flooding, over-evaporation, spillage, breakage, overflow, loss of flow, etc., etc.) When the range of credible concentrations has been decided for the system, the range of the critical parameter for these concentrations can be read off from the selected curves of that parameter. After choosing the smallest value of the critical parameter from this range the safe value is derived by multiplying by the safety factor given on the page facing the figure. It should be noted that all dimensions are metric, and that the cylinder dimension given is the radius. At enrichments below 5% it is also necessary to decide whether the system considered is effectively homogeneous. Attention should not be confined only to the particular curve of critical parameter being examined. It is frequently informative to examine two or more curves concurrently. Thus, if a precipitate is being collected in a fixed volume container it would be informative to examine the critical mass curve as well as the critical volume curve, since clearance on safe volume can be more restrictive than clearance according to safe mass for high concentrations and vice-versa for low concentrations.

The Handbook is not intended to be a comprehensive work, and covers only the more commonly occurring problems. Should problems occur which do not appear to be covered by it, or if any doubt regarding its correct application arises, expert advice should be sought from the appropriate specialist group.

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SECTION B: Criticality data for plutonium-239 systems

1. The critical parameters given for plutonium systems are based on limited experimental data. A few experiments were done several years ago to determine the minimum critical mass of plutonium in nitrate solution. British experimental results have been published,(1) and some similar American results became available at the first Geneva Conference.(2) In addition to these, only two other experiments are known. The first is an estimate, from a sub-critical assembly, of the critical mass of plutonium in a PuO_2-paraffin wax mixture at an H/Pu atomic ratio of 50:1,(3) and the second is an estimate of the critical mass of solid plutonium metal(4) at a density of 19·2 g/cm^3.

2. From these few experiments the curves showing critical parameters for all plutonium concentrations have been calculated. In the derivation of the curves it has been assumed that the mixture of fissile material and moderator was α-phase ^{239}Pu metal and water. Consequently, corrections to the experimental results have included allowances for the effects of nitrate ion and the ^{240}Pu isotope. Extensions of the data have been made to estimate minimum infinite slab thickness and minimum infinite cylinder diameter, using the equal buckling relation.(5)

3. The data are accurate in the range of solution concentrations up to 0·250 g Pu/cm^3 (H/Pu $\geqslant$ 100) and also for solid metal. For plutonium concentrations between 0·250 g/cm^3 and the solid metal state the critical parameters have been estimated cautiously (i.e. values are less than the probable critical figures).

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5. PERKS, M.A., et al. Criticality of plutonium metal-water systems. 1959. IG Memorandum 244 (RD/R)

NOTES ON THE USE OF FIGS B1-4

Critical parameter curves ^{239}Pu

(i) The curves can be used for solutions, mixtures of water and α-phase metal, and mixtures of water and all plutonium compounds except plutonium hydride (see section G).

(ii) The curves can be used for homogeneous and heterogeneous systems (the safety factor recommended is adequate to cover any effect from the variable concentration type of heterogeneity).

(iii) Spot values are given of the H/Pu ratio at certain plutonium concentrations. The continuous variation of this ratio with concentration is shown in Fig. B5. Also indicated are the following four approximate physical regions:

(a) Solutions of concentrations normally encountered in chemical plants (i.e. up to 0·300-0·350 g/cm^3).

(b) Concentrated solutions up to 0·750-0·800 g/cm^3.

(c) Intermediate densities, which includes sludges and precipitates of fluorides and nitrates (i.e. up to about 6 g/cm^3).

(d) High densities, which covers oxides, metallic alloys, δ-phase metal and α-phase metal of a density up to 19·2 g/cm^3.

(iv) The curves relate to single fully water-reflected vessels free from neutron interaction.

Note on the use of Fig. B1. Critical mass curve

The maximum safe mass of plutonium is three-quarters of the smallest critical mass for the worst credible conditions.

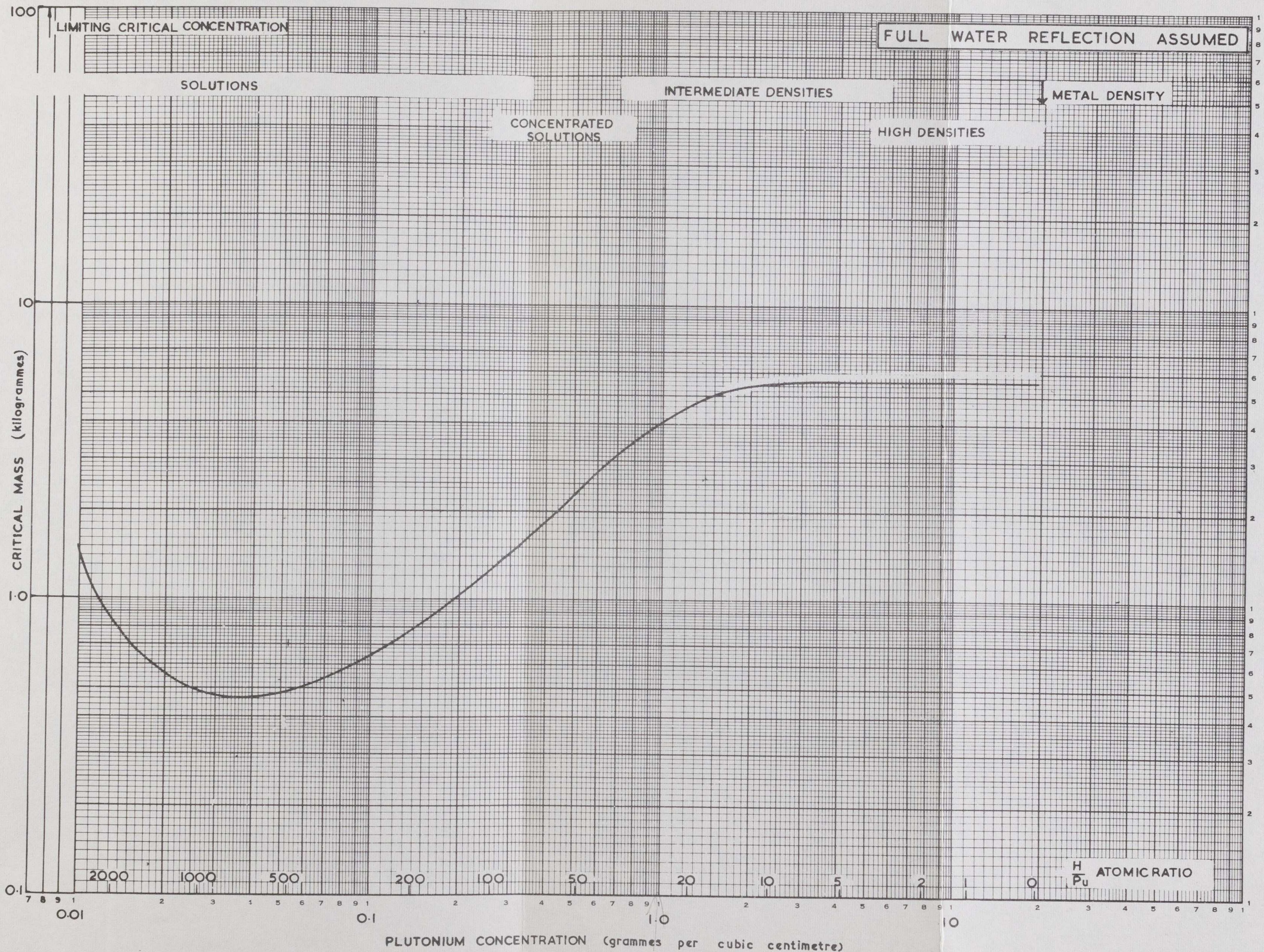

FIG. B1 SMALLEST CRITICAL MASS AGAINST PLUTONIUM CONCENTRATION FOR ^{239}Pu

Note on the use of Fig. B2.   Critical volume curve

The maximum safe volume is three-quarters of the smallest critical volume for the worst credible conditions.

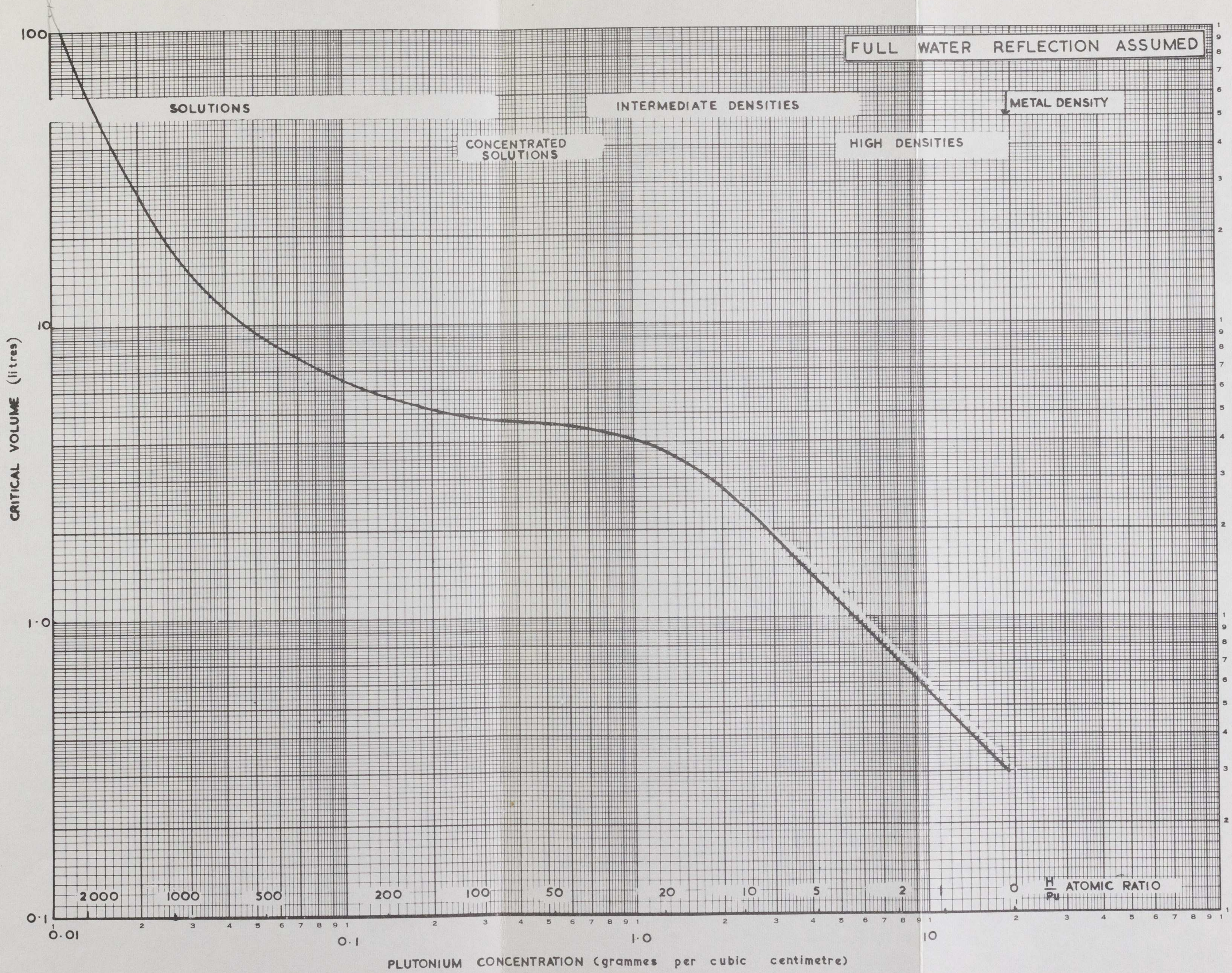

FIG. B2 SMALLEST CRITICAL VOLUME AGAINST PLUTONIUM CONCENTRATION FOR ^{239}Pu

Note on the use of Fig. B3. Critical cylinder radius curve

The maximum safe cross-sectional area of a cylinder is three-quarters of the smallest critical cross-sectional area for the worst credible conditions (i.e. the safe cylinder radius is 85% of the critical radius).

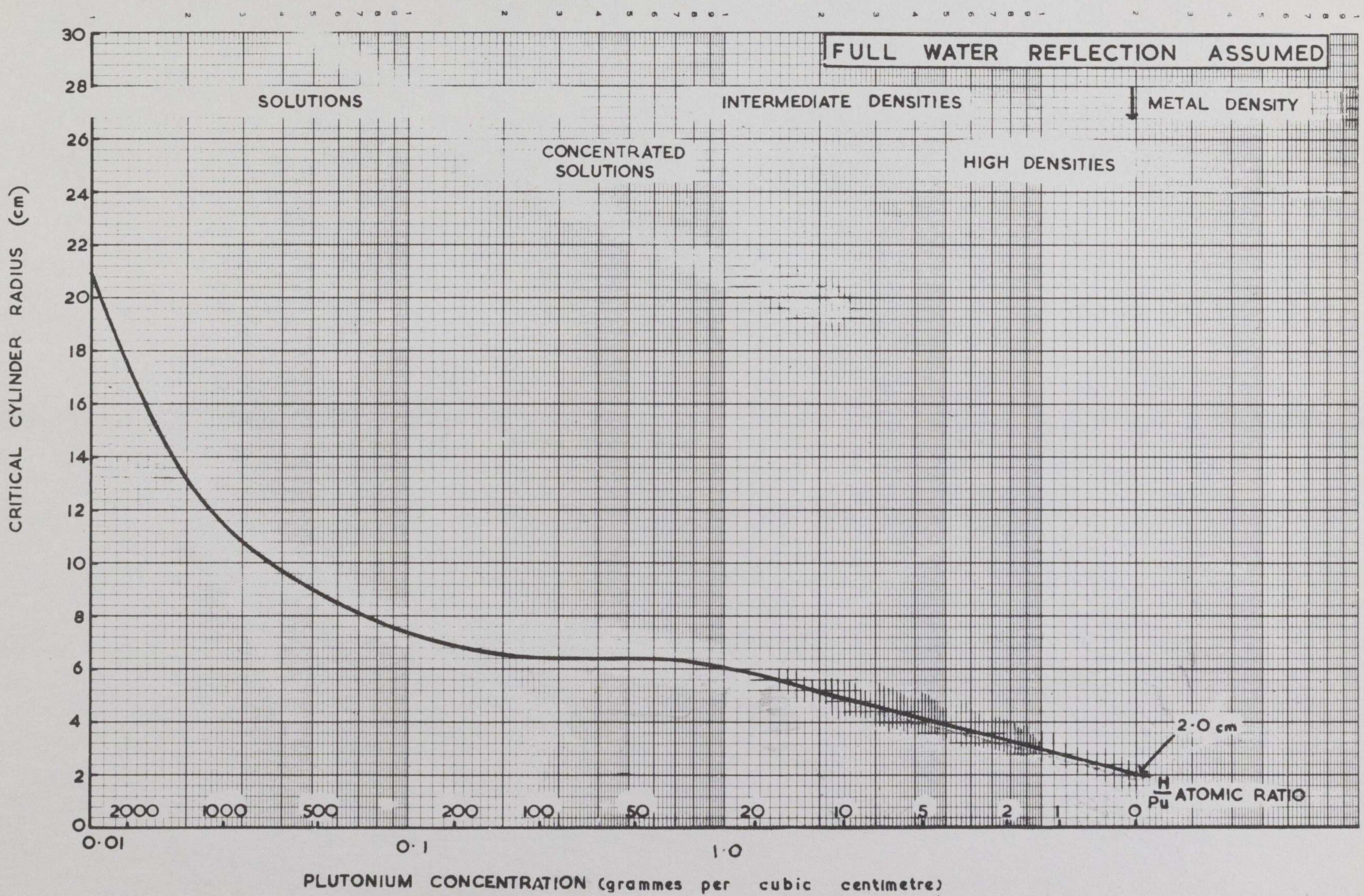

FIG. B3 SMALLEST CRITICAL RADIUS OF INFINITE CYLINDER AGAINST PLUTONIUM CONCENTRATION FOR ^{239}Pu

Note on the use of Fig. B4. Critical slab thickness curve

The maximum safe slab thickness is three-quarters of the smallest critical slab thickness for the worst credible conditions.

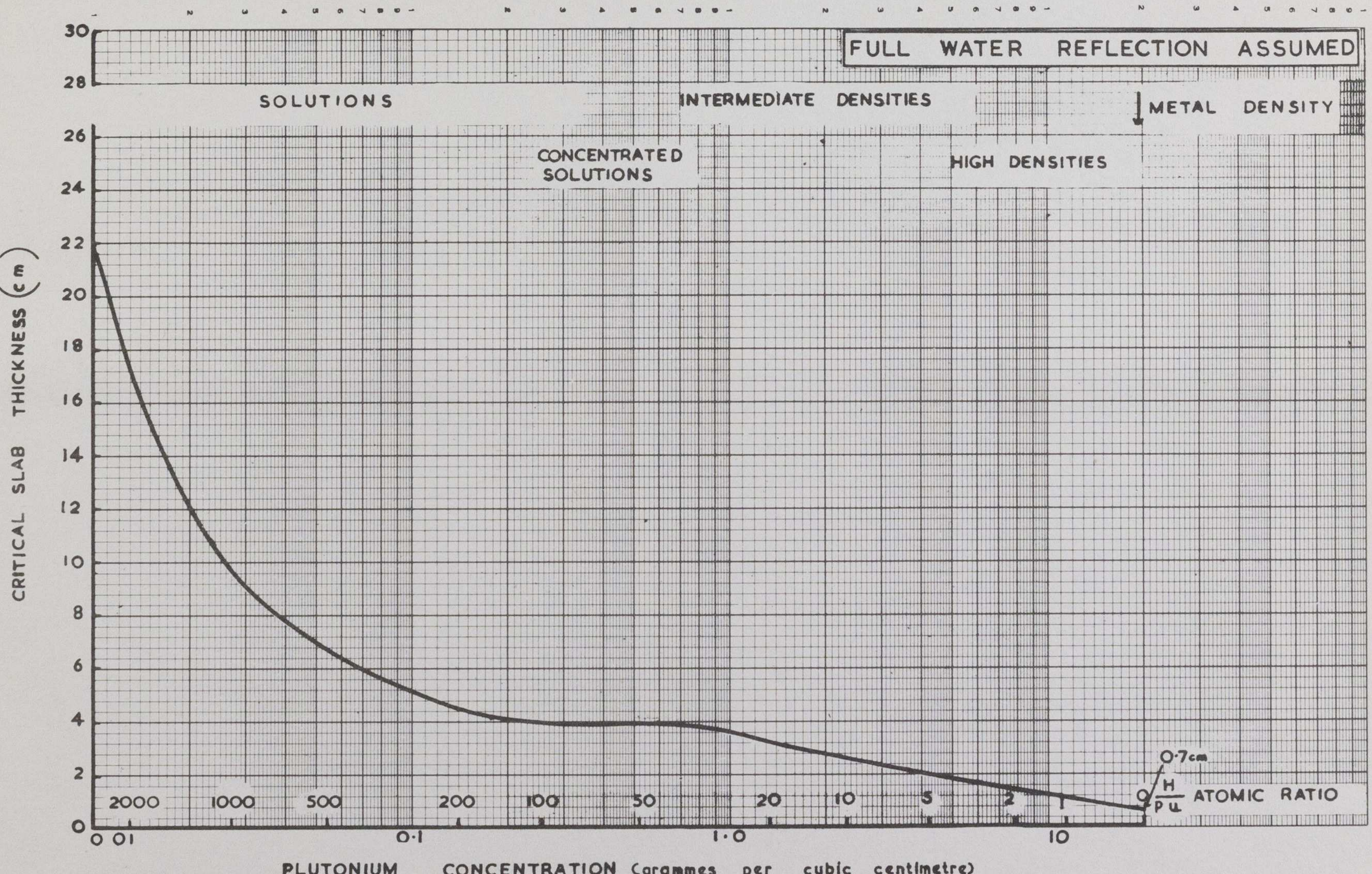

FIG. B4 SMALLEST CRITICAL THICKNESS OF INFINITE SLAB AGAINST PLUTONIUM CONCENTRATION FOR ^{239}Pu

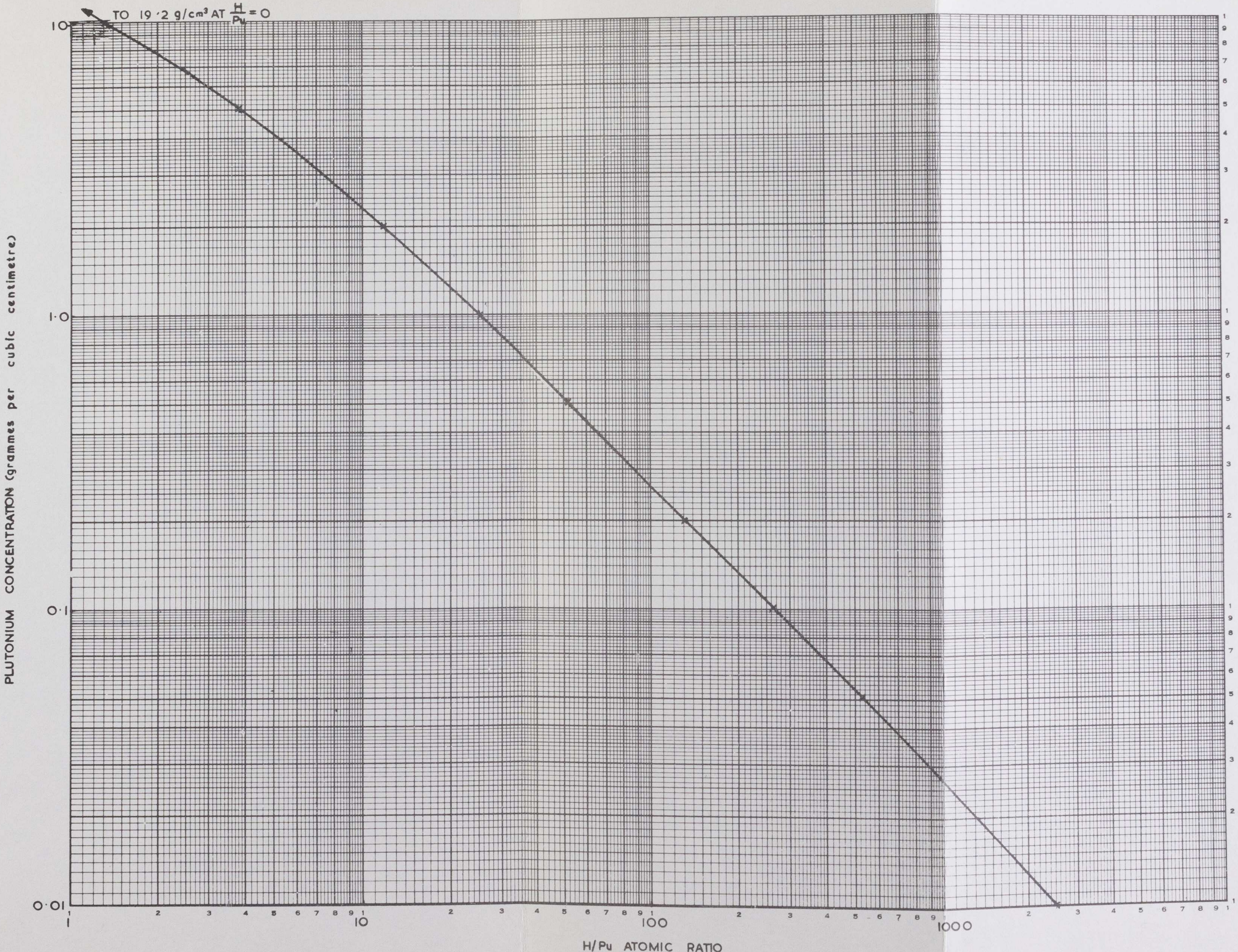

FIG. B 5 PLUTONIUM CONCENTRATION AGAINST H/Pu ATOMIC RATIO FOR METAL– WATER MIXTURES

SECTION C: Criticality data for uranium systems within the ^{235}U enrichment range 30 - 93%

1. This enrichment range for uranium systems is the one which is most fully covered by experimental data on homogeneous solutions, particularly at the extreme enrichments.

The data have been derived from experiments with aqueous uranyl fluoride (UO_2F_2) solutions which, owing to the large dilution by water (uranium concentration less than 0·8 g/cm^3 and H/U atomic ratio greater than 30), give results indistinguishable from those calculated for metal-water mixtures. Critical parameters based on metal-water mixtures will be slightly pessimistic compared with all other uranium solutions.

2. A considerable amount of experimental data is available on solutions with an enrichment of 93·2% ^{235}U. Results for solutions in aluminium spheres are given in four reports(1-4) covering H/^{235}U ratios from 50 to 1270. Results for both aluminium and stainless steel cylinders are given in five reports(3,5-8) covering a similar range. One result(9) for a Lucite-reflected slab at an H/^{235}U ratio of 44·7 is also available. The data for cylinders whose height and diameter were approximately equal were converted(10) to spherical geometry and checked independently(11) using the equal-buckling relation. Close agreement was found between the two sets of results, so that an accurate curve of critical mass against uranium concentrations could be drawn(11) for 93% ^{235}U solutions with H/U ratios above 20.

3. Also available for an enrichment of 93% ^{235}U are two results(12-13) for uranium hydride cubes with a natural uranium metal reflector. These results have been converted(10) for density and reflector effectiveness so as to be applicable to a water-reflected metal-water mixture. The resulting points at H/^{235}U ratios of 3 and 15 are quoted as uncertain by about 5%. This conversion has also been checked independently and good agreement found. The metal critical mass(14) is accurately known at an enrichment of 93·5% ^{235}U and a density of 18·8 g/cm^3.

The curve of 93% ^{235}U critical mass against uranium concentration can therefore be drawn with an estimated error of less than 5% for the solution range and at the metal limit, and of less than 10% in the intermediate region.

4. Experimental results for two other enrichments have been reported. At 44·6% ^{235}U, experiments with solutions in a stainless-steel cylinder have been performed(15) at three different H/^{235}U ratios spanning the minimum mass. Using the buckling conversion, the minimum mass for a fully water-reflected sphere can then be found. At 30·3% ^{235}U, a series of experiments on stainless-steel cylinders covering H/^{235}U ratios from 75 to 950 have been performed.(16) These data have also been converted to spherical geometry by the equal-buckling relation.

5. Further experimental data are available over a wide enrichment range for solid metal. The data include results on bare and natural-uranium-reflected spheres at enrichments from 29 to 93% ^{235}U,(17) results at 45·5% ^{235}U(18) and 16·25% ^{235}U(19) from which the bare spherical mass can be deduced, and also results from exponential columns(14) at lower enrichments. These results, together with the calculated limiting enrichment for pure metal of 5-6% ^{235}U, define fairly accurately the variation of bare critical mass with enrichment.

Conversion to full water-reflection can be made with confidence at high enrichments. Thus the metal critical mass is known down to an enrichment of about 15% ^{235}U to within 10%. At the other end of the moderation scale, the limiting critical concentrations (due to hydrogen dilution) can easily be calculated thus locating the positions of the asymptotes to the critical mass and other critical parameter curves.

6. The enrichments chosen for presentation of the data in this section are 30, 50 and 93% ^{235}U. The derivation of the curve of 93% ^{235}U critical mass against concentration has been described fully.[11] From the associated critical volume curve the infinite cylinder radius and infinite slab thickness curves have been derived[11] using the equal-buckling relation. The estimated accuracy of these curves is within 10% on mass, volume, cylinder area and slab thickness. All the 93% ^{235}U curves agree well with other published data.[20]

7. The extension of the critical mass data at 30% ^{235}U to all $H/^{235}U$ ratios has been described elsewhere.[21] In the same Report can be found the derivation of the 50% ^{235}U critical mass curve and also that of the cylinder radius and slab thickness curves at both enrichments. The data at these two enrichments were derived from experiments using solutions in stainless-steel cylinders, which give slightly higher critical parameters than do solutions in aluminium cylinders. This effect, however, is significant only for slab-shaped vessels and the usual safety factor would cover the difference. With this reservation in mind, the estimated accuracy of these 30% ^{235}U and 50% ^{235}U curves (for stainless-steel vessels) may be taken as 10% on mass, volume, cylinder area and slab thickness.

8. The minimum critical mass in the 30-93% enrichment range occurs in the solution region. The least critical volume, cylinder radius and slab thickness occur for solid metal. There is, however, a local minimum for these three parameters in the solution range. This local minimum has the same value as that for solid metal at an enrichment of about 27% ^{235}U.

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NOTES ON THE USE OF FIGS C1-4

Critical parameter curves 30-93% ^{235}U

(i) The curves can be used for solutions, mixtures of water and metal, and mixtures of water and all uranium compounds except uranium hydride (see section G).

(ii) The curves can be used for homogeneous and heterogeneous systems (the safety factor recommended is adequate to cover any effect from the variable concentration type of heterogeneity).

(iii) Spot values are given of the H/U atomic ratio at certain uranium concentrations. The continuous variation of this ratio with concentration is shown in Fig. C5. Also indicated are the following four approximate physical regions:

- (a) Solutions of concentrations normally encountered in chemical plants (i.e. up to 0·25-0·30 g/cm^3).
- (b) Concentrated solutions up to the solubility limit of 1-1·2 g/cm^3.
- (c) Intermediate densities, which includes sludges and precipitates of fluorides and nitrates (i.e. up to about 5 g/cm^3).
- (d) High densities, which covers oxides, metallic alloys and metal (i.e. up to 18·8 g/cm^3).

(iv) The curves relate only to single fully water-reflected vessels free from neutron interaction.

Note on the use of Fig. C1. Critical mass curves

The maximum safe mass of uranium is three-quarters of the smallest critical mass for the worst credible conditions.

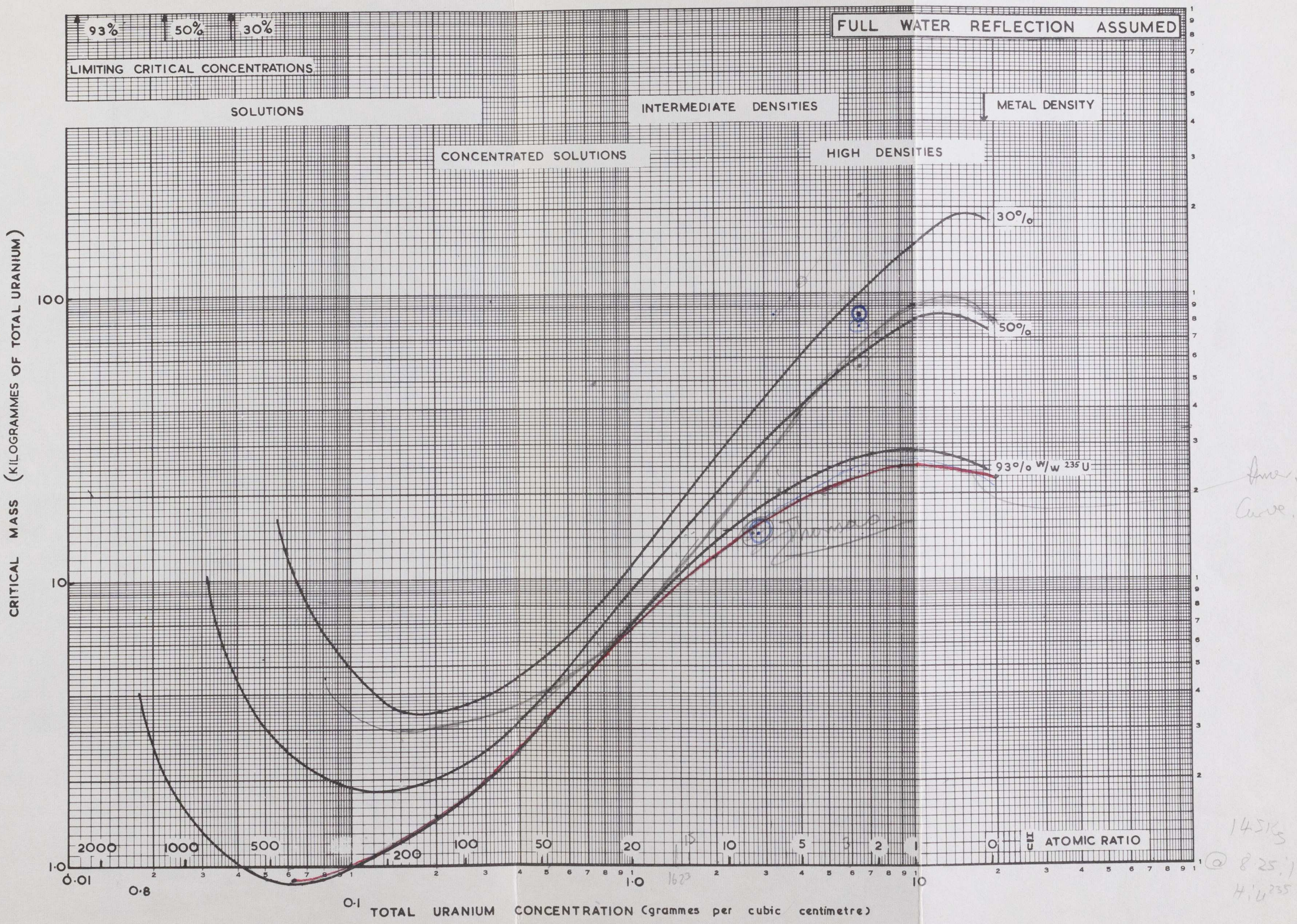

FIG. C1 SMALLEST CRITICAL MASS AGAINST URANIUM CONCENTRATION FOR 30, 50, 93% W/w 235U

Note on the use of Fig. C2. Critical volume curves

The maximum safe volume is three-quarters of the smallest critical volume for the worst credible conditions.

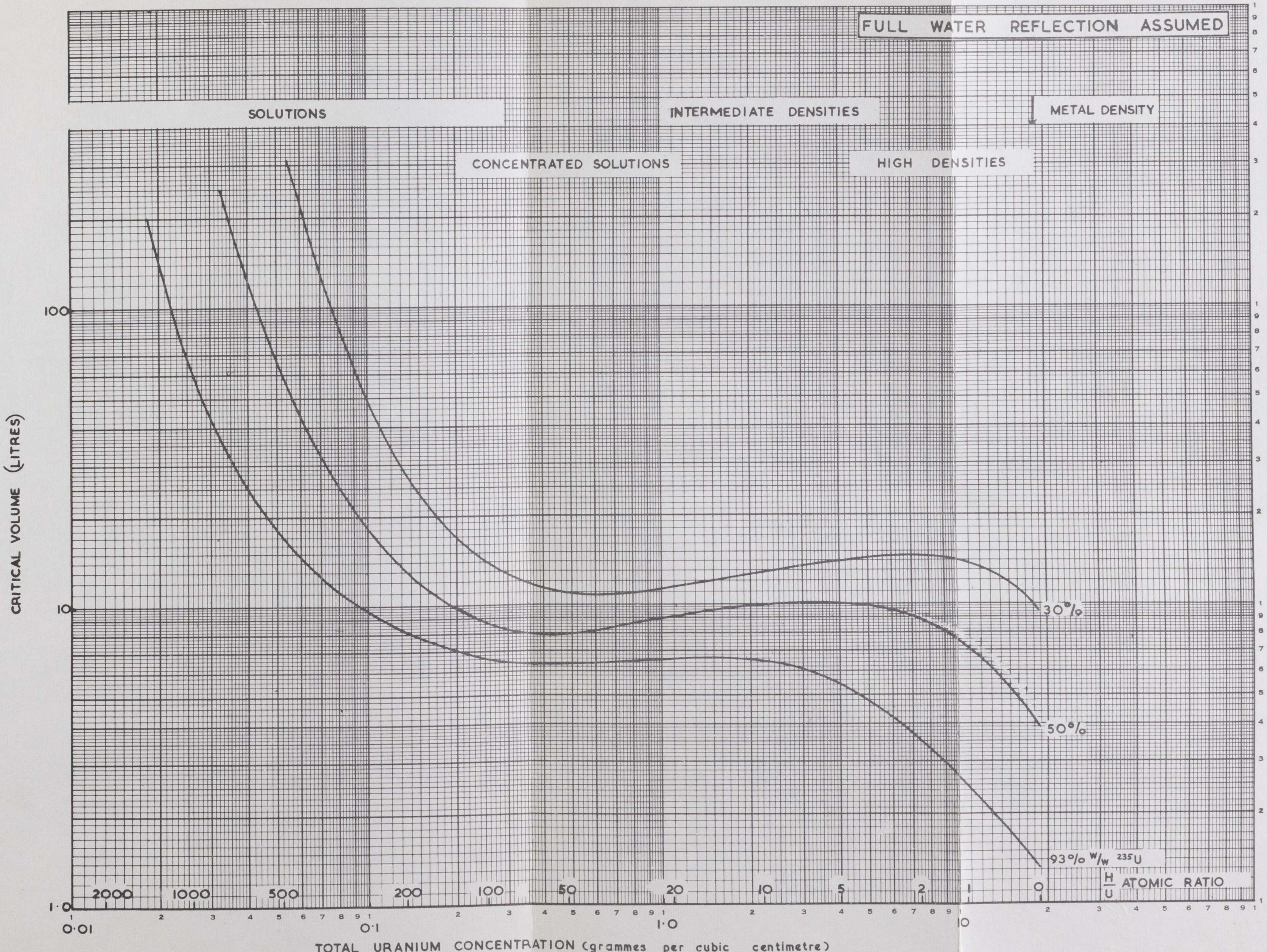

FIG. C2 SMALLEST CRITICAL VOLUME AGAINST URANIUM CONCENTRATION FOR 30, 50, 93% W/W ^{235}U

Note on the use of Fig. C3. Critical cylinder radius curves

The maximum safe cross-sectional area of a cylinder is three-quarters of the smallest critical cross-sectional area for the worst credible conditions (i.e. the safe cylinder radius is 85% of the critical radius).

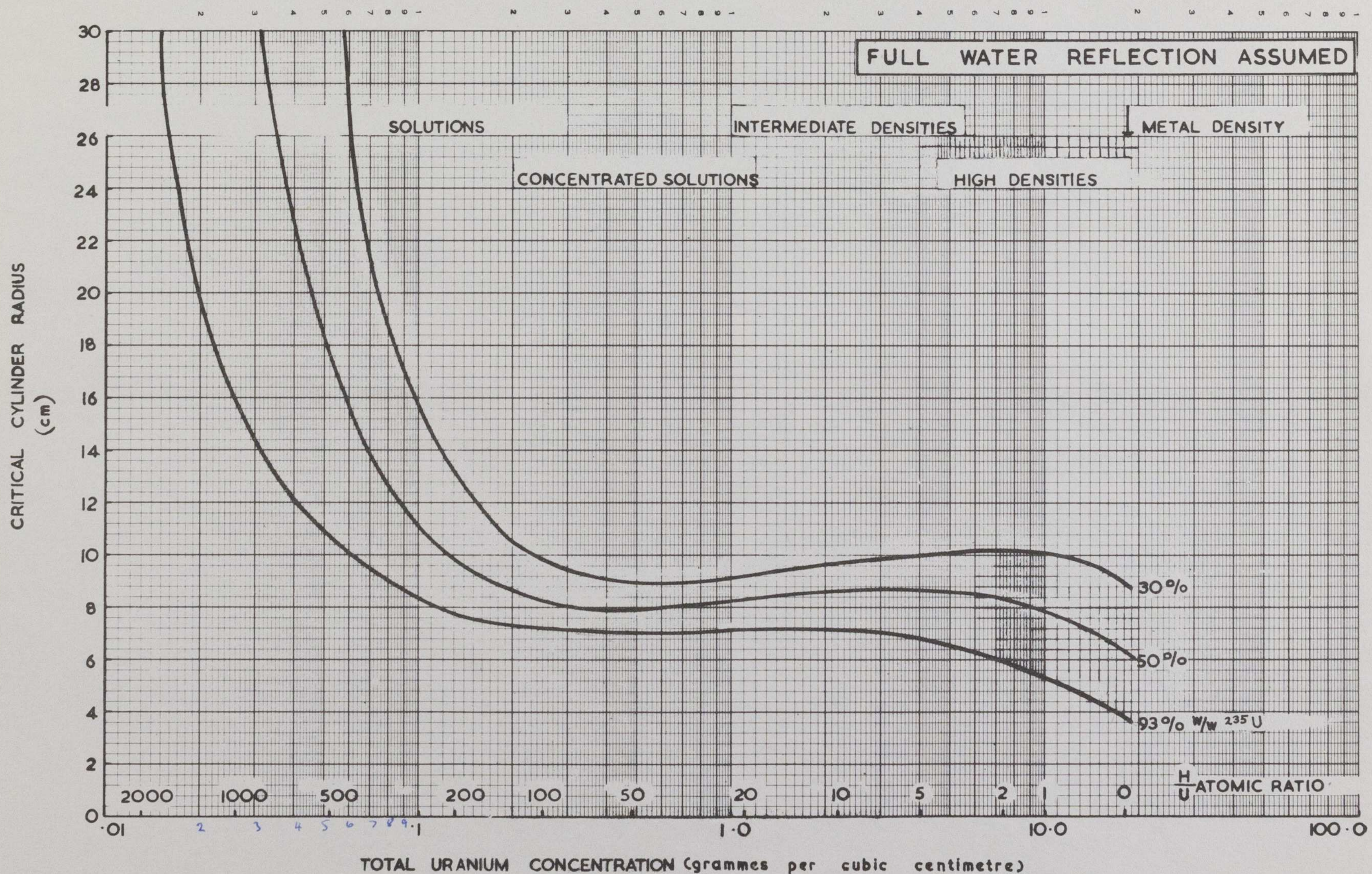

FIG. C3 SMALLEST CRITICAL INFINITE CYLINDER RADIUS AGAINST URANIUM CONCENTRATION FOR 30, 50, 93% W/w 235U

Note on the use of Fig. C4. Critical slab thickness curves

The maximum safe slab thickness is three-quarters of the smallest critical slab thickness for the worst credible conditions.

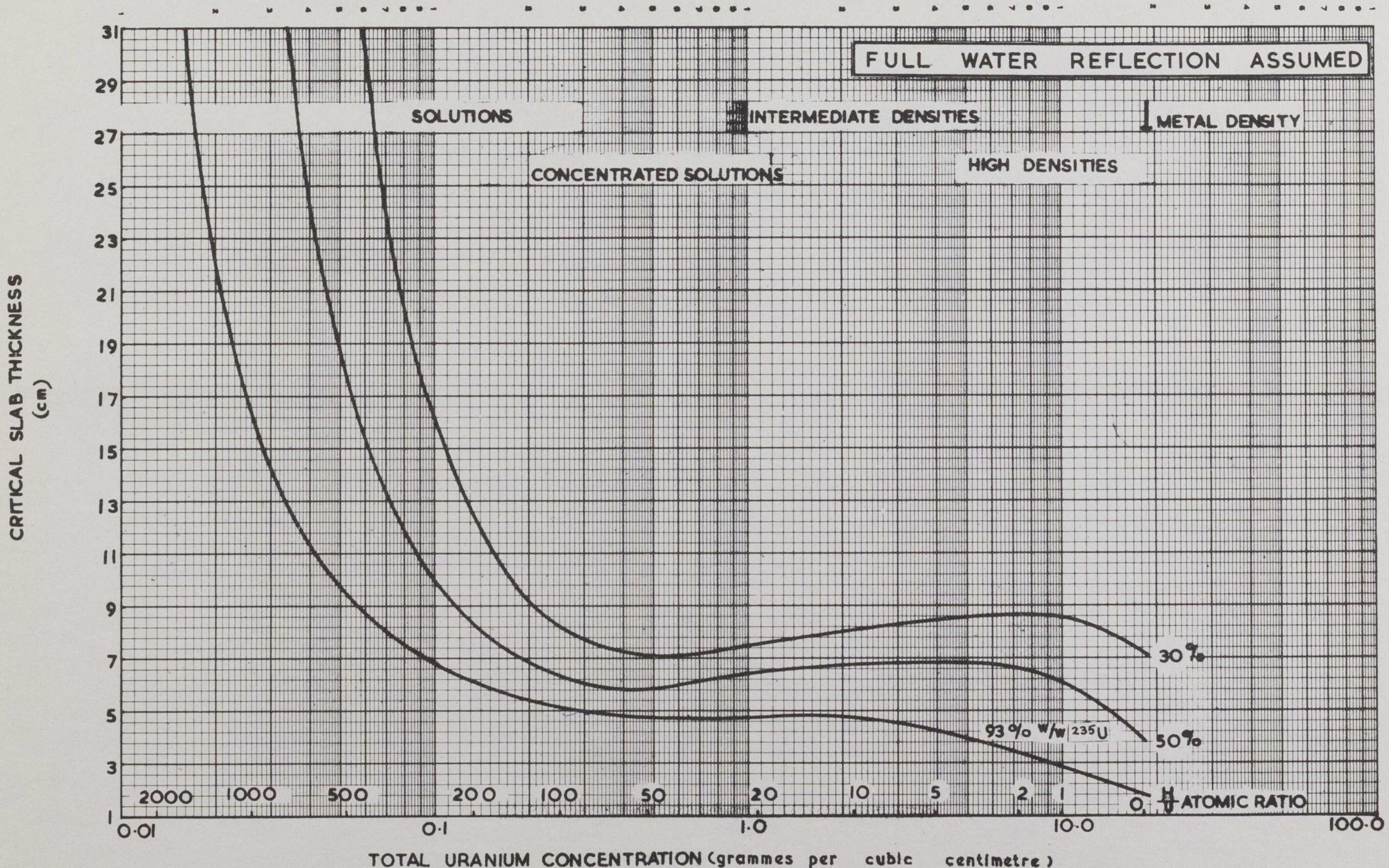

FIG. C4 SMALLEST CRITICAL INFINITE SLAB THICKNESS AGAINST URANIUM CONCENTRATION FOR 30, 50, & 93 % $^{W}/_{W}$ ^{235}U

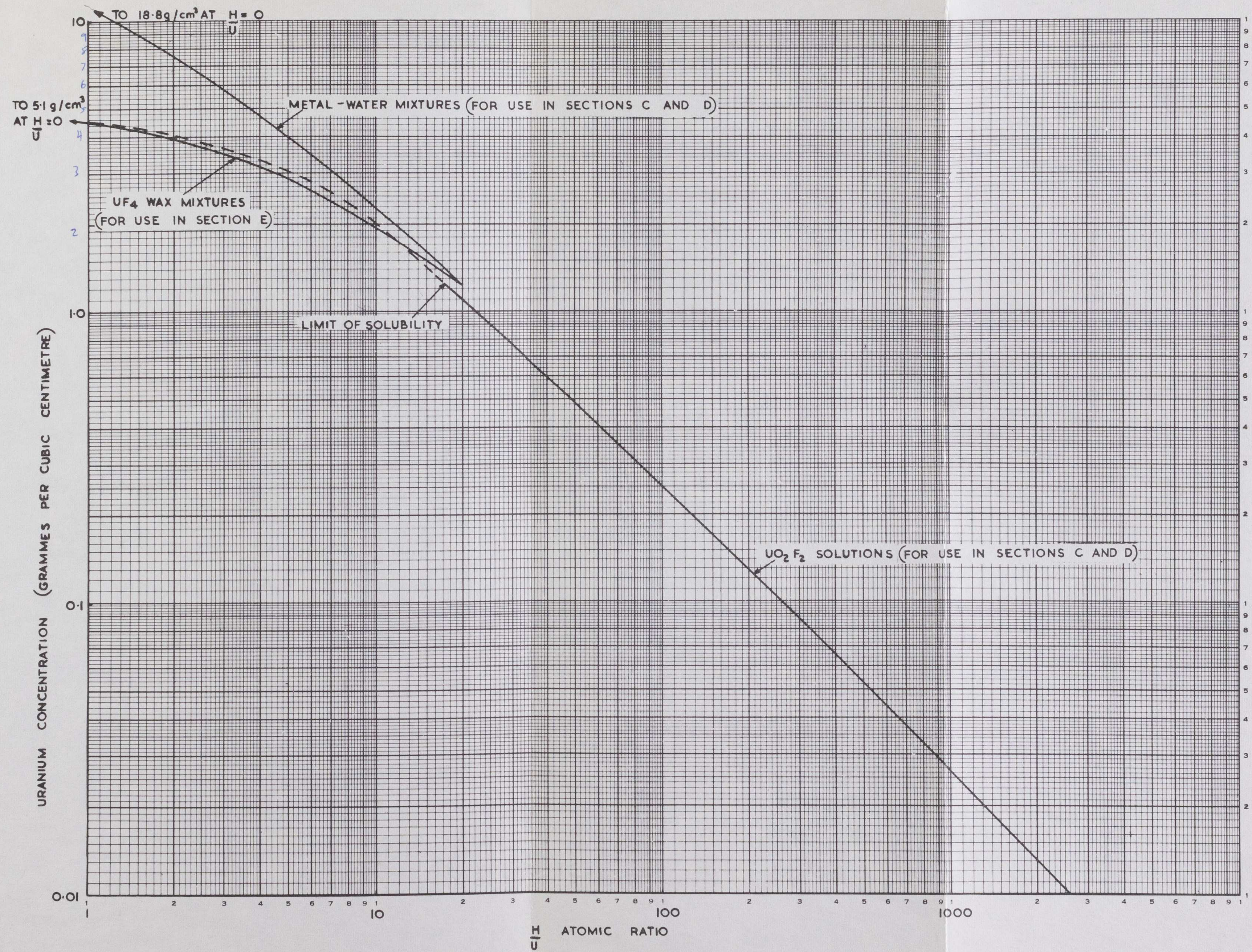

FIG. C5 URANIUM CONCENTRATION AGAINST $\frac{H}{U}$ ATOMIC RATIO FOR UO_2F_2 SOLUTIONS, METAL-WATER MIXTURES AND UF_4- WAX MIXTURES

SECTION D: Criticality data for uranium systems within the ^{235}U enrichment range 5 - 30%

1. This enrichment range is the least well covered by reliable experimental data. One experimental result at an enrichment of 14·7% ^{235}U[1,2] is available. This experiment employed a UO_2SO_4 solution in a stainless-steel sphere at an $H/^{235}U$ ratio of 650. The result yields an estimate of the minimum critical mass. A series of experiments were performed at an enrichment of 4·9% ^{235}U[3,4] using a UO_2F_2 solution in both aluminium and stainless steel cylinders. The $H/^{235}U$ range covered was 530 to 1200. Since the minimum critical mass occurs below this range, the experiments were extended to a $H/^{235}U$ ratio of 130, using a U_3O_8-glycerol tri-stearate mixture. This mixture has a lower uranium concentration at a given H/U ratio than the solution. Hence the results had to be corrected for this effect. The usual reduction to spherical geometry was also made.

2. The enrichments chosen for presentation of the data in this section are 5, 7, 10 and 15% ^{235}U, data at 30% ^{235}U having already been presented in section C. The experimental critical mass data described above have been extended to all $H/^{235}U$ ratios for all these enrichments.[5] The results for 15% ^{235}U are considered reliable over the whole $H/^{235}U$ range (this is the lowest enrichment at which the metal critical mass is reasonably well known). For the three lower enrichments the data are not considered sufficiently reliable to use for safety purposes at very low H/U ratios and are therefore indicated by broken curves on the appropriate graphs. The approximate ends of the curves are shown as guides to the trends of the data at the metal limits. The critical volume curves have been derived from the mass curves, and the infinite cylinder radius and infinite slab thickness curves have been obtained in the usual way.[5]

3. The minimum critical mass occurs in the solution range for all enrichments, although at 5% ^{235}U it occurs almost at the limit of saturation. The minima agree well with other published data.[1,4] The minimum critical volume, cylinder radius and slab thickness occur in the solution range for 10% and 15% ^{235}U and in the intermediate density range for 5% and 7% ^{235}U.

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NOTES ON THE USE OF FIGS D1-4

Critical parameter curves 5-30% ^{235}U

(i) The curves can be used for solutions, mixtures of water and metal, and mixtures of water and all uranium compounds except uranium hydride (see section G).

(ii) Spot values are given of the H/U atomic ratio at certain uranium concentrations. The continuous variation of this ratio with concentration is shown in Fig. C5. Also indicated are the following four approximate physical regions:

- (a) Solutions of concentrations normally encountered in chemical plants (i.e. up to 0·25-0·30 g/cm^3)
- (b) Concentrated solutions up to the solubility limit of 1-1·2 g/cm^3
- (c) Intermediate densities, which includes sludges and precipitates of fluorides and nitrates (i.e. up to about 5 g/cm^3)
- (d) High densities, which covers oxides, metallic alloys and metal (i.e. up to 18·8 g/cm^3).

(iii) The curves relate only to single fully water-reflected vessels free from neutron interaction.

Notes on the use of Fig. D1. Critical mass curves

The curves can be used for homogeneous and heterogeneous systems under the following conditions:

(1) In the concentration ranges covered by the solid parts of the curves the maximum safe mass of uranium is three-quarters of the smallest critical mass for the worst credible conditions.

(2) In the concentration ranges in which the curves are broken, the safe mass of uranium to be used is three-quarters of the smallest critical mass at the maximum concentration end of the solid curve.

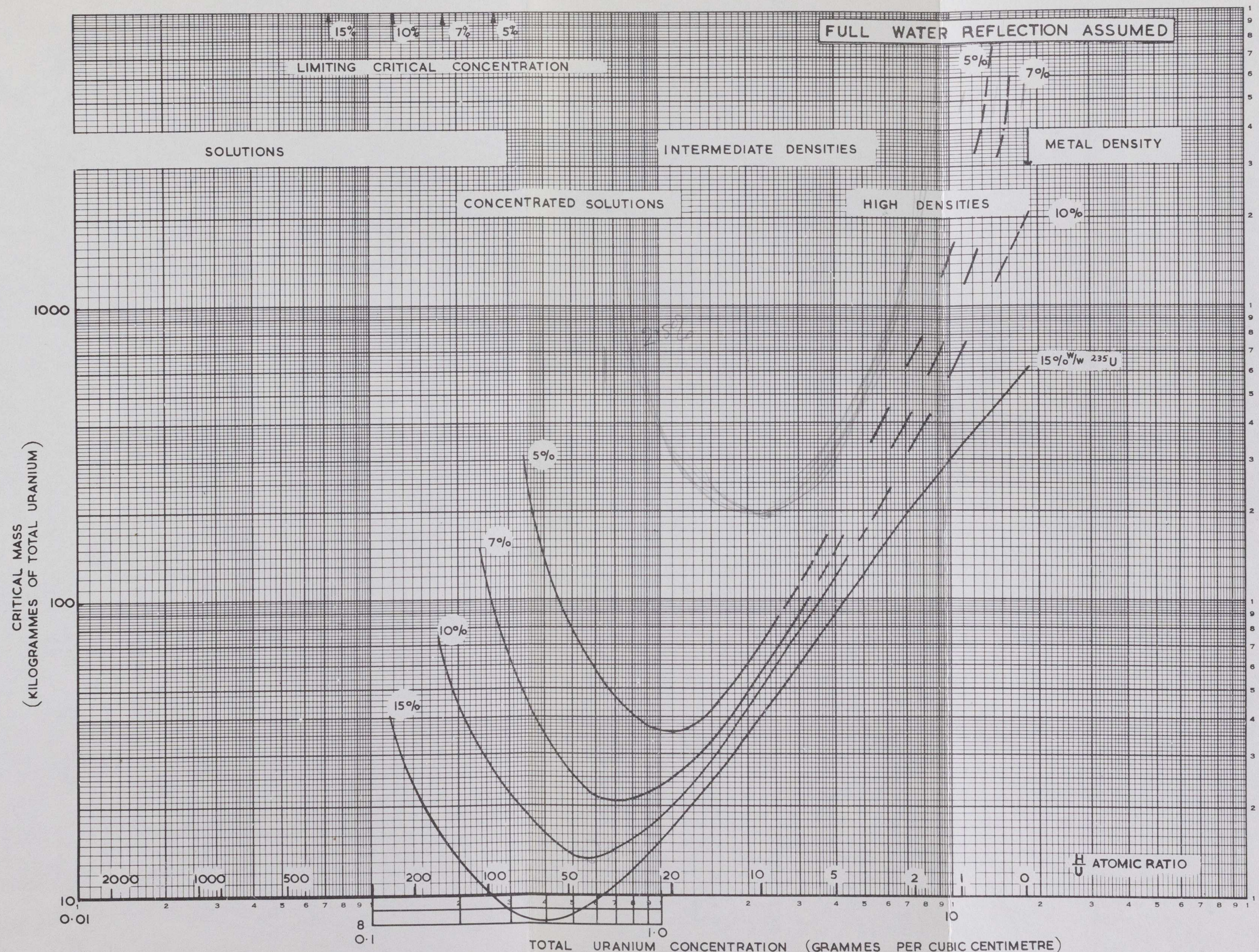

FIG. D1 SMALLEST CRITICAL MASS AGAINST URANIUM CONCENTRATION FOR 5, 7, 10, 15% W/W ^{235}U

Notes on the use of Fig. D2. Critical volume curves

The curves can be used for homogeneous systems under the following conditions:

(1) In the concentration ranges covered by the solid parts of the curves the maximum safe volume is three-quarters of the smallest critical volume for the worst credible conditions.

(2) In the concentration ranges in which the curves are broken, the safe volume to be used is three-quarters of the smallest critical volume, at the maximum concentration end of the solid curve.

The curves can be used for heterogeneous systems under the following conditions (the safety factor recommended is adequate to cover any effect from the lattice type of heterogeneity):

(3) In the concentration ranges covered by the solid parts of the curves the maximum safe volume is two-thirds of the smallest critical volume, for the worst credible conditions.

(4) In the concentration ranges in which the curves are broken, the safe volume to be used is two-thirds of the smallest critical volume, at the maximum concentration end of the solid curve.

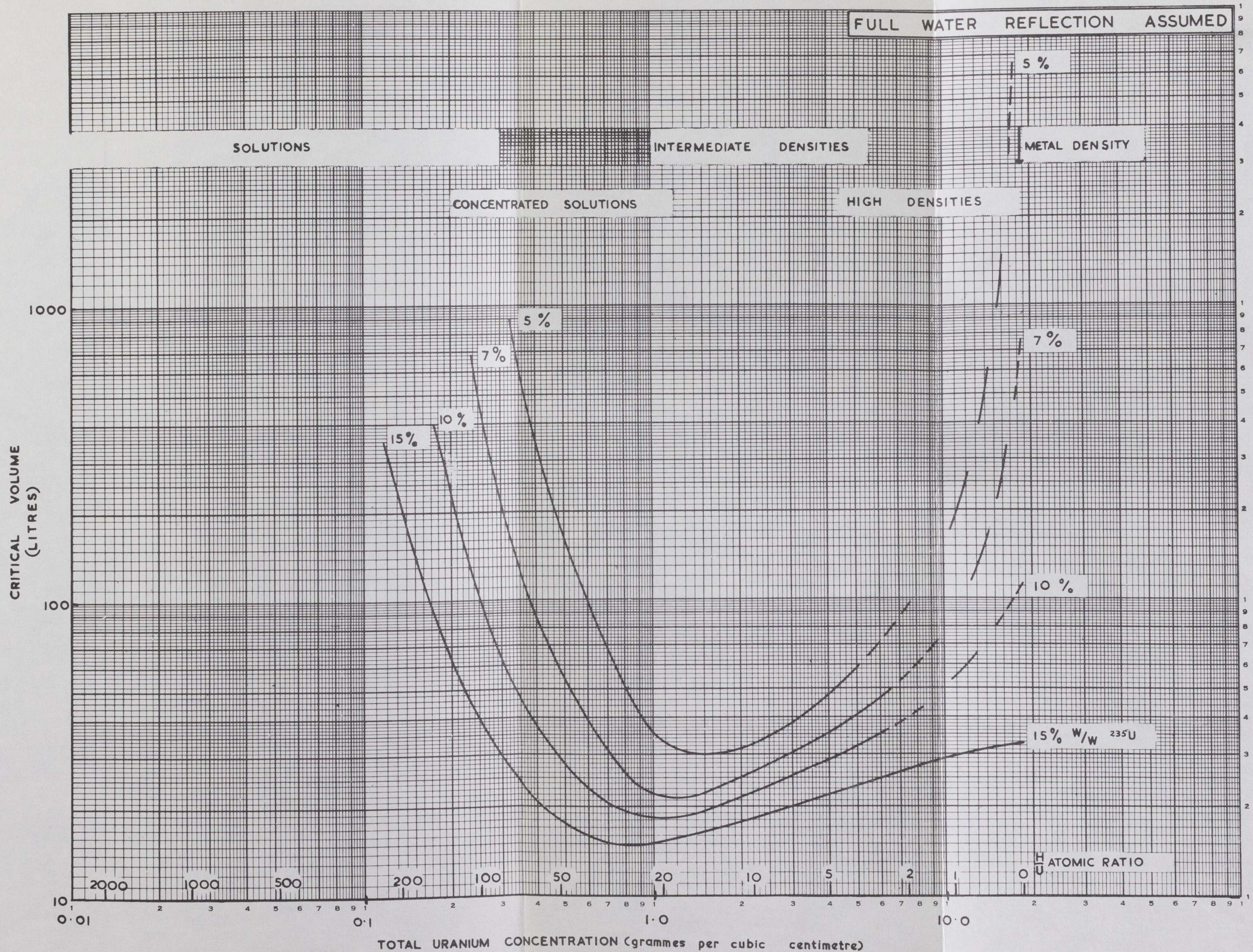

FIG. D2 SMALLEST CRITICAL VOLUME AGAINST URANIUM CONCENTRATION FOR 5, 7, 10, 15 % W/W 235U

Notes on the use of Fig. D3. Critical cylinder radius curves

The curves can be used for homogeneous systems under the following conditions:

(1) In the concentration ranges covered by the solid parts of the curves the maximum safe cross-sectional area of a cylinder is three-quarters of the smallest critical cross-sectional area for the worst credible conditions (i.e. the safe cylinder radius is 85% of the critical radius).

(2) In the concentration ranges in which the curves are broken, the safe cross-sectional area of a cylinder to be used is three-quarters of the smallest critical cross-sectional area at the maximum concentration end of the solid curve (i.e. the safe cylinder radius is 85% of the critical radius).

The curves can be used for heterogeneous systems under the following conditions (the safety factor recommended is adequate to cover any effect from the lattice type of heterogeneity):

(3) In the concentration ranges covered by the solid parts of the curves the maximum safe cross-sectional area of a cylinder is two-thirds of the smallest critical cross-sectional area for the worst credible conditions (i.e. the safe cylinder radius is 80% of the critical radius).

(4) In the concentration ranges in which the curves are broken, the safe cross-sectional area of a cylinder to be used is two-thirds of the smallest critical cross-sectional area at the maximum concentration end of the solid curve, (i.e. the safe cylinder radius is 80% of the critical radius).

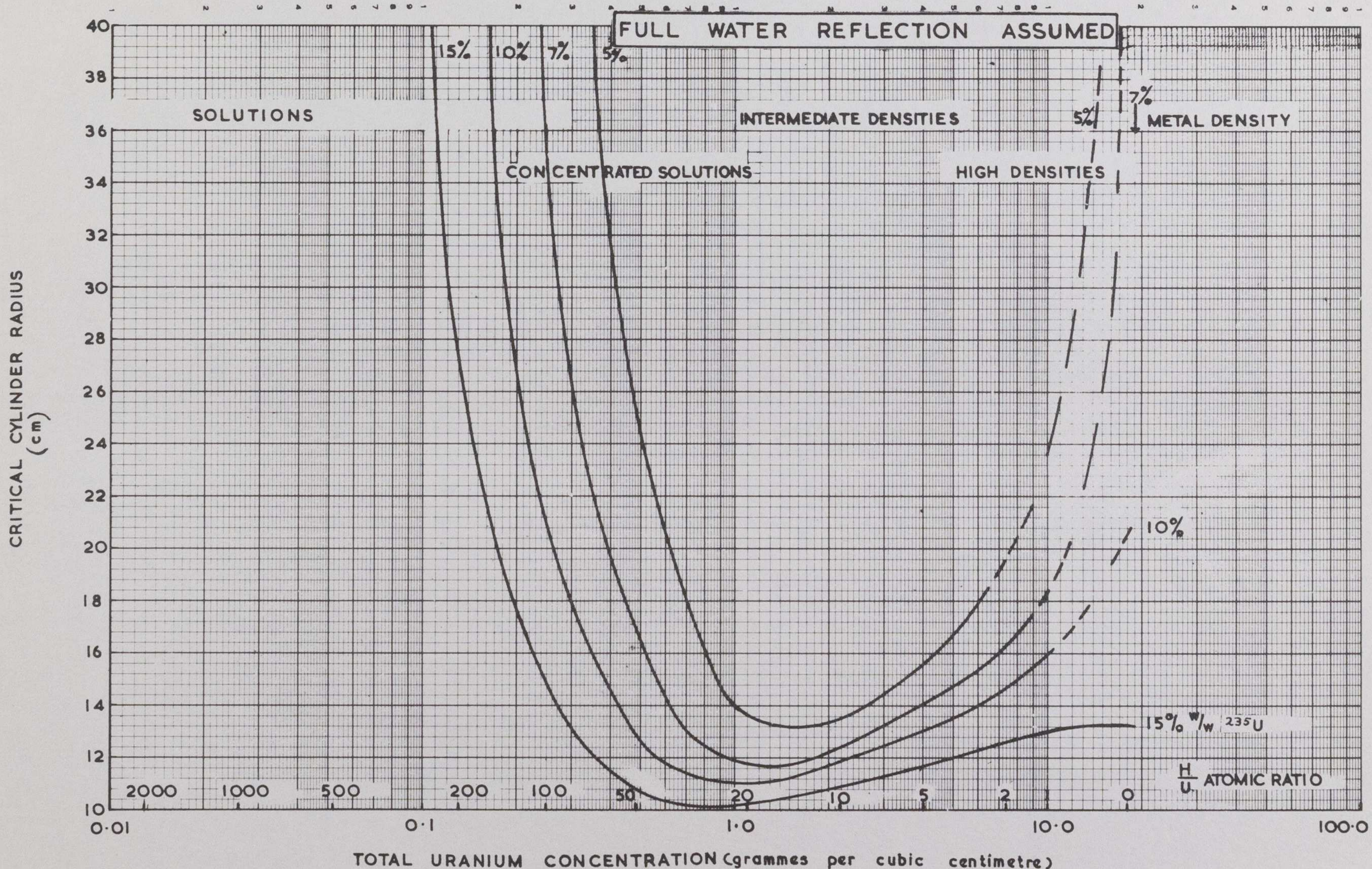

FIG. D3 SMALLEST CRITICAL INFINITE CYLINDER RADIUS AGAINST URANIUM CONCENTRATION FOR 5, 7, 10, 15% $^{W}/_{W}$ ^{235}U

Notes on the use of Fig. D4. Critical slab thickness curves

The curves can be used for homogeneous systems under the following conditions:

(1) In the concentration ranges covered by the solid parts of the curves the maximum safe slab thickness is three-quarters of the smallest critical slab thickness for the worst credible conditions.

(2) In the concentration ranges in which the curves are broken, the safe slab thickness to be used is three-quarters of the smallest critical slab thickness at the maximum concentration end of the solid curve.

The curves can be used for heterogeneous systems under the following conditions (the safety factor recommended is adequate to cover any effect from the lattice type of heterogeneity):

(3) In the concentration ranges covered by the solid parts of the curves the maximum safe slab thickness is two-thirds of the smallest critical slab thickness for the worst credible conditions.

(4) In the concentration ranges in which the curves are broken, the safe slab thickness to be used is two-thirds of the smallest critical slab thickness at the maximum concentration end of the solid curve.

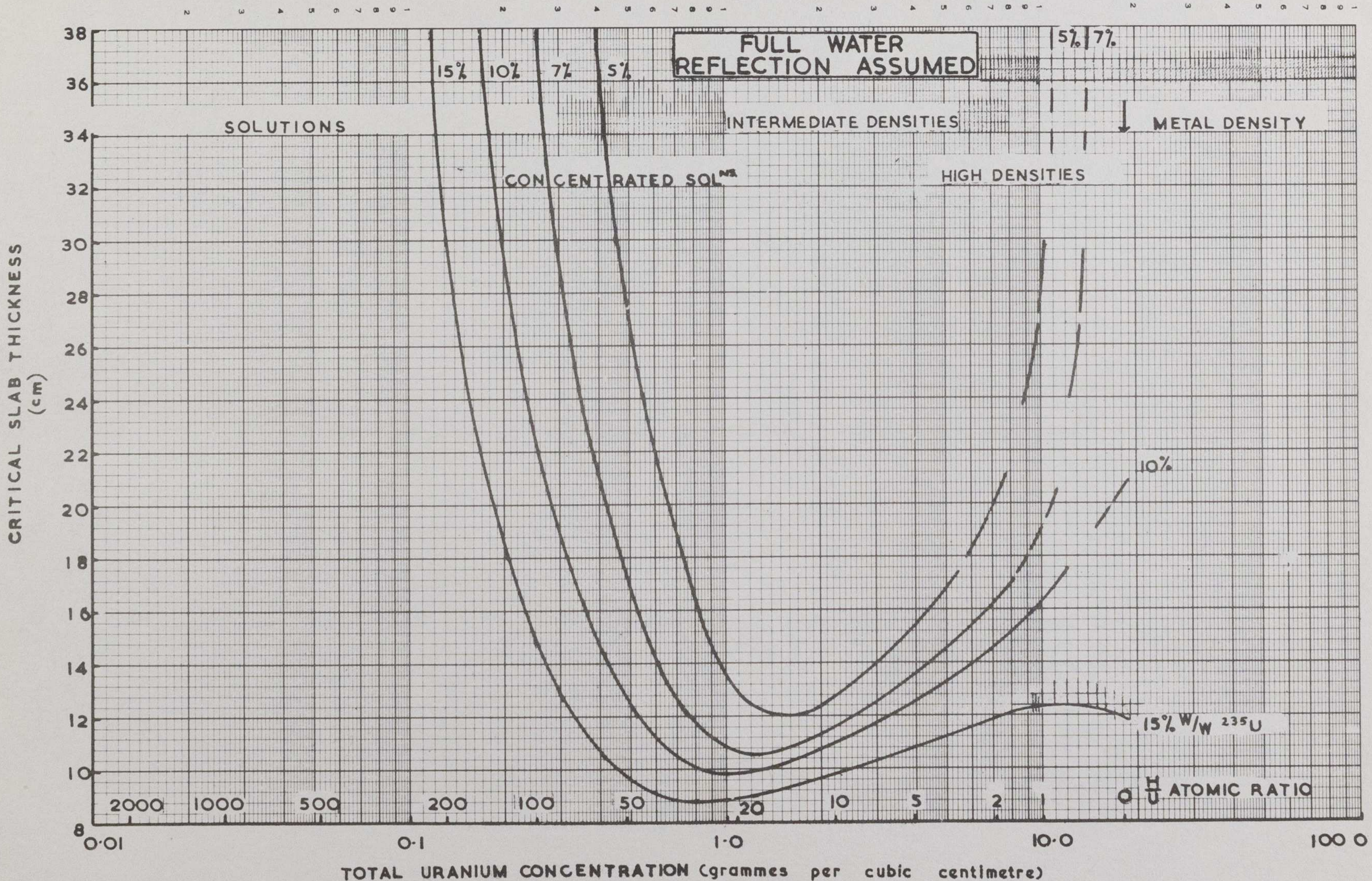

FIG. D4 SMALLEST CRITICAL INFINITE SLAB THICKNESS AGAINST URANIUM CONCENTRATION FOR 5,7,10,15% W/W ^{235}U

SECTION E: Criticality data for uranium systems with ^{235}U enrichments of less than 5%

Note: Read also section A.

There are a number of unique features affecting the presentation of critical data for uranium systems where the ^{235}U enrichment is less than 5% by weight of the total uranium.

1. Solid uranium metal cannot be made critical within this range of enrichments no matter what the reflector may be,[1] though it is well known that lattice arrangements of uranium metal or oxide and moderator (water or graphite for example) can be made critical.[2-6]

In casting operations, most designs of graphite crucible can be cleared on the basis of solid metal systems reflected by graphite. In general, the fracture of a crucible presents no additional hazard because it is considered that any assembly of graphite and uranium that can be formed by this means cannot be made critical.

A further precaution that must be taken where a number of dimensionally small uranium systems may be placed in close array in graphite containers is that the formation of a lattice must be avoided.

2. By implication it follows that any physical form of uranium other than metal that is not moderated cannot be made critical. Such systems must be guaranteed to remain dry and unmoderated.

3. A special system in dry form that must be considered is beryllium cladding on metal or oxide fuel elements. If the uranium rod size is maintained at 0·3 in. diameter or greater, and the thickness of beryllium cladding does not exceed 0·050 in., any assembly will remain subcritical if maintained dry. If an assembly of such fuel elements can become flooded by water, the critical data presented for lattice assemblies should be used for assessments of safety.[7]

4. For mixtures or systems that can be moderated by hydrogenous media (of which water is assumed to be the most dangerous), two principal types of system are considered. First, there are systems of low or intermediate uranium concentration in which it is assumed, for homogeneous mixtures of uranium and water, that the maximum credible concentration of uranium that can be obtained at a given H/U atomic ratio will not exceed that obtained by fabricating pressed blocks of homogeneously mixed UF_4 and paraffin wax* (see Fig. C5). This specification covers conditions arising in most chemical plant processes (important exceptions are dissolvers where oxides and metals can be present).[8] Conditions which fall within this range have their minimum critical parameters shown by the curves marked "homogeneous" in Figs E1-4. Minimum critical parameters for these conditions occur in regions beyond the saturation concentration for solutions (H/U atomic ratio < 20). Experimental determinations of critical parameters have been made using UF_4-paraffin wax blocks[9,10] and calculations have been made to determine the limiting critical dimensions of slabs and cylinders.[11]

*Density 0·9 g/cm³. Composition CH_2.

5. For systems where the uranium concentrations in homogeneous mixtures can be appreciably higher, at given H/U atomic ratios, than that of the UF_4-wax mixtures or, particularly, where the uranium can be present in solid forms of metal (or metallic alloys or oxide) interspersed with water, the worst credible critical condition must be taken as a lattice of metal rods moderated by water[12] (a metal dissolver or a swarf storage container if flooded by water will come under this category). The appropriate minimum critical parameters are shown by the curves marked "Lattice" in Figs E1-4.

6. In addition to the minimum parameters presented in Figs E1-4 the variation of critical mass, etc. with uranium concentration for homogeneous mixtures based on UF_4-paraffin wax experiments is shown in Figs E5-8. These curves are given for enrichments of 1·4%, 2%, 3% and 4% ^{235}U. The curves for the first two enrichments are based on experiment[9,10] and those for the second two on theoretical extrapolation.[13] The curves are shown in full only down to an H/U ratio of 4. Beyond this the data are regarded as too uncertain for safety assessments and only an indication of the way the curves tend to the limiting concentration is shown.

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NOTES ON THE USE OF FIGS E1-4

Minimum critical parameter curves less than 5% ^{235}U

(i) The curves marked "homogeneous" can be used for homogeneous and randomly heterogeneous solutions and mixtures of uranium compounds, as specified in paragraph 4.

(ii) The curves marked "lattice" can be used for heterogeneous assemblies of water and any solid uranium compound including metal.

(iii) The curves refer to a single fully water-reflected vessel free from neutron interaction.

(iv) The limiting critical enrichment is 1·0% ^{235}U for homogeneous systems and 0·7% ^{235}U for lattice systems.

Note on the use of Fig. E1. Minimum critical mass curve

The maximum safe mass of uranium is three-quarters of the minimum critical mass for the appropriate type of system.

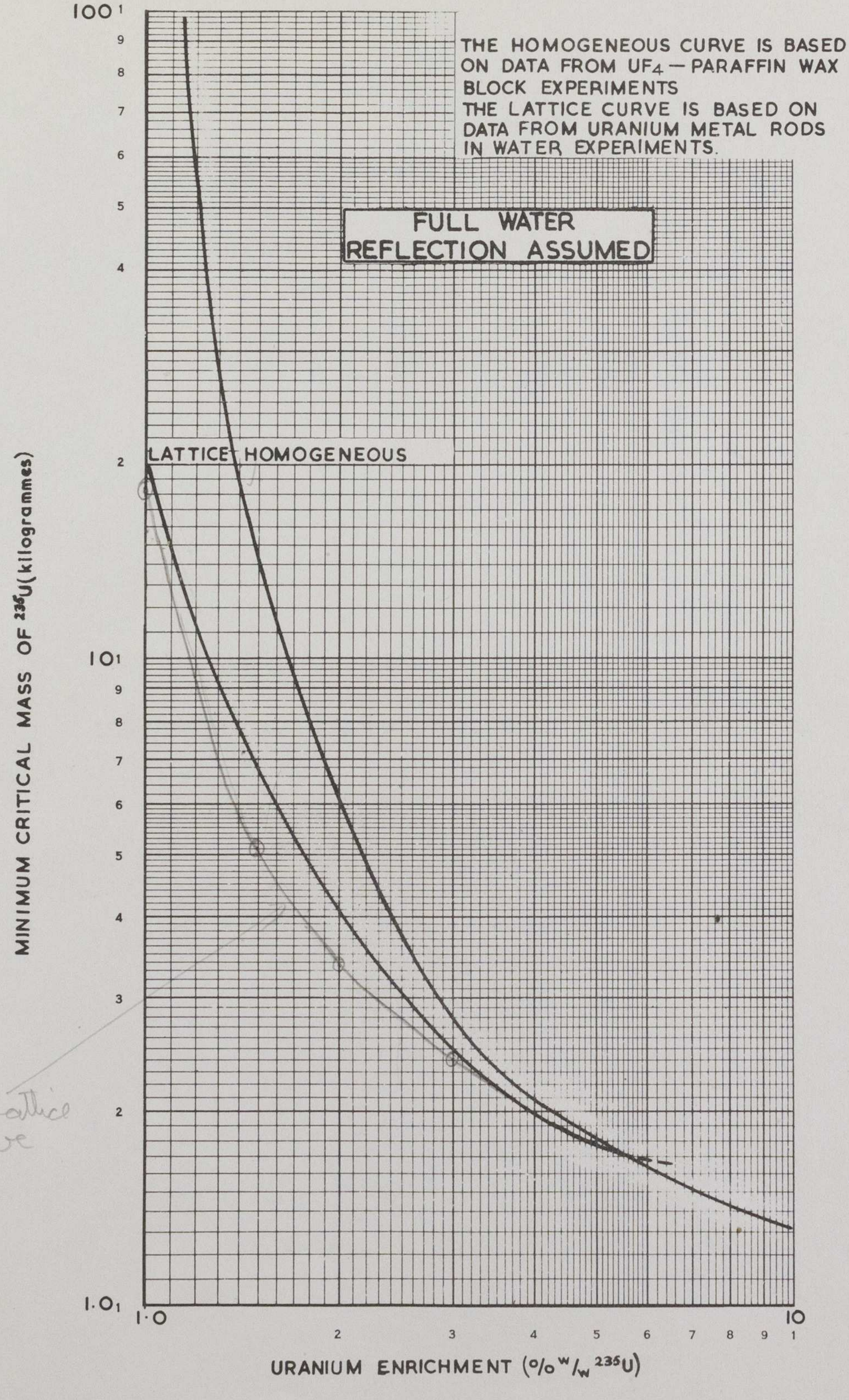

FIG. E1 MINIMUM CRITICAL MASS AGAINST ENRICHMENT FOR LESS THAN 5% w/w ^{235}U

Note on the use of Fig. E2. Minimum critical volume curve

The maximum safe volume is three-quarters of the minimum critical volume for the appropriate type of system.

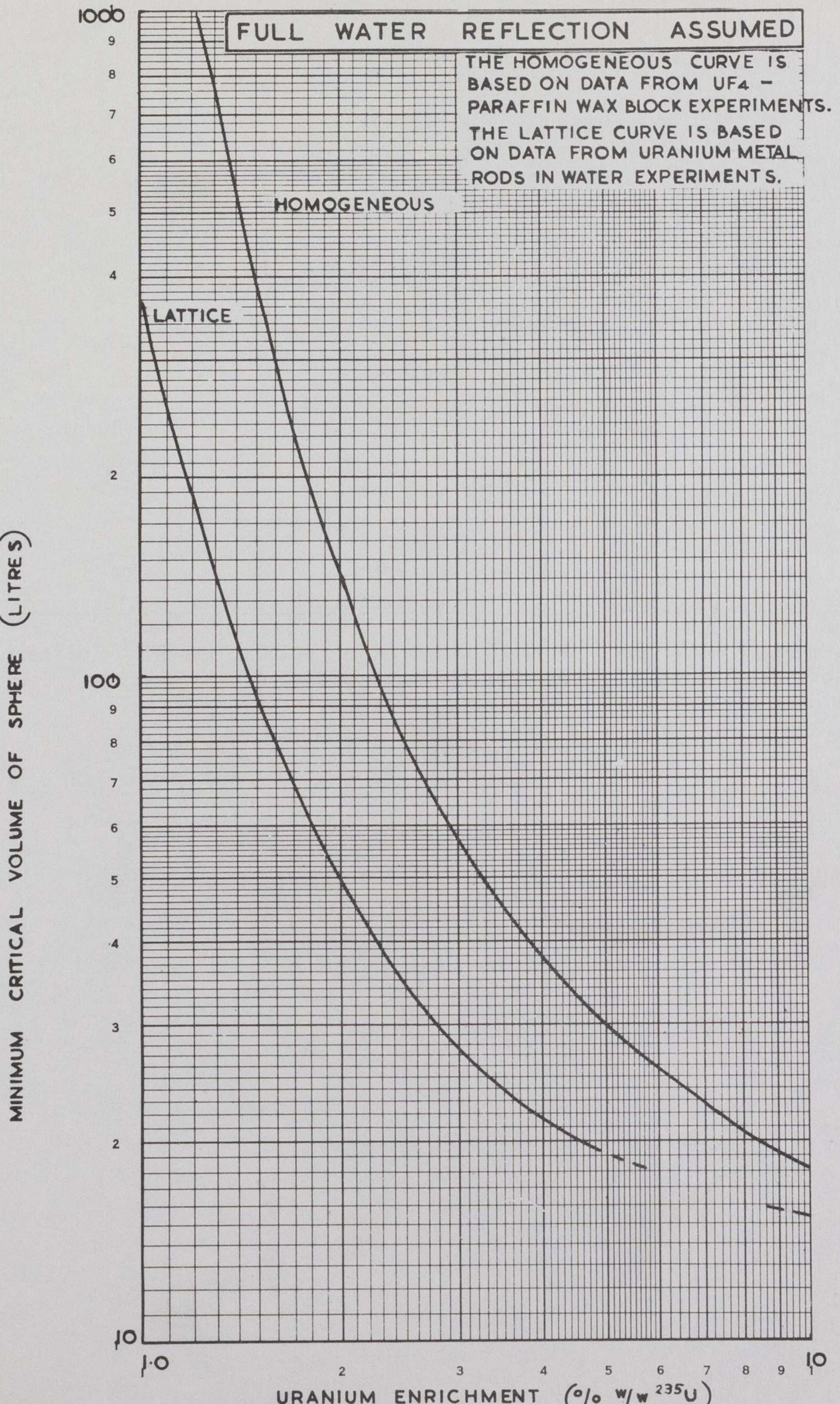

FIG. E2 MINIMUM CRITICAL VOLUME AGAINST ENRICHMENT FOR LESS THAN 5 % w/w ^{235}U

Note on the use of Fig. E3. Minimum critical cylinder radius curve

The maximum safe cross-sectional area of a cylinder is three-quarters of the minimum cross-sectional area for the appropriate type of system (i.e. the safe cylinder radius is 85% of the critical one).

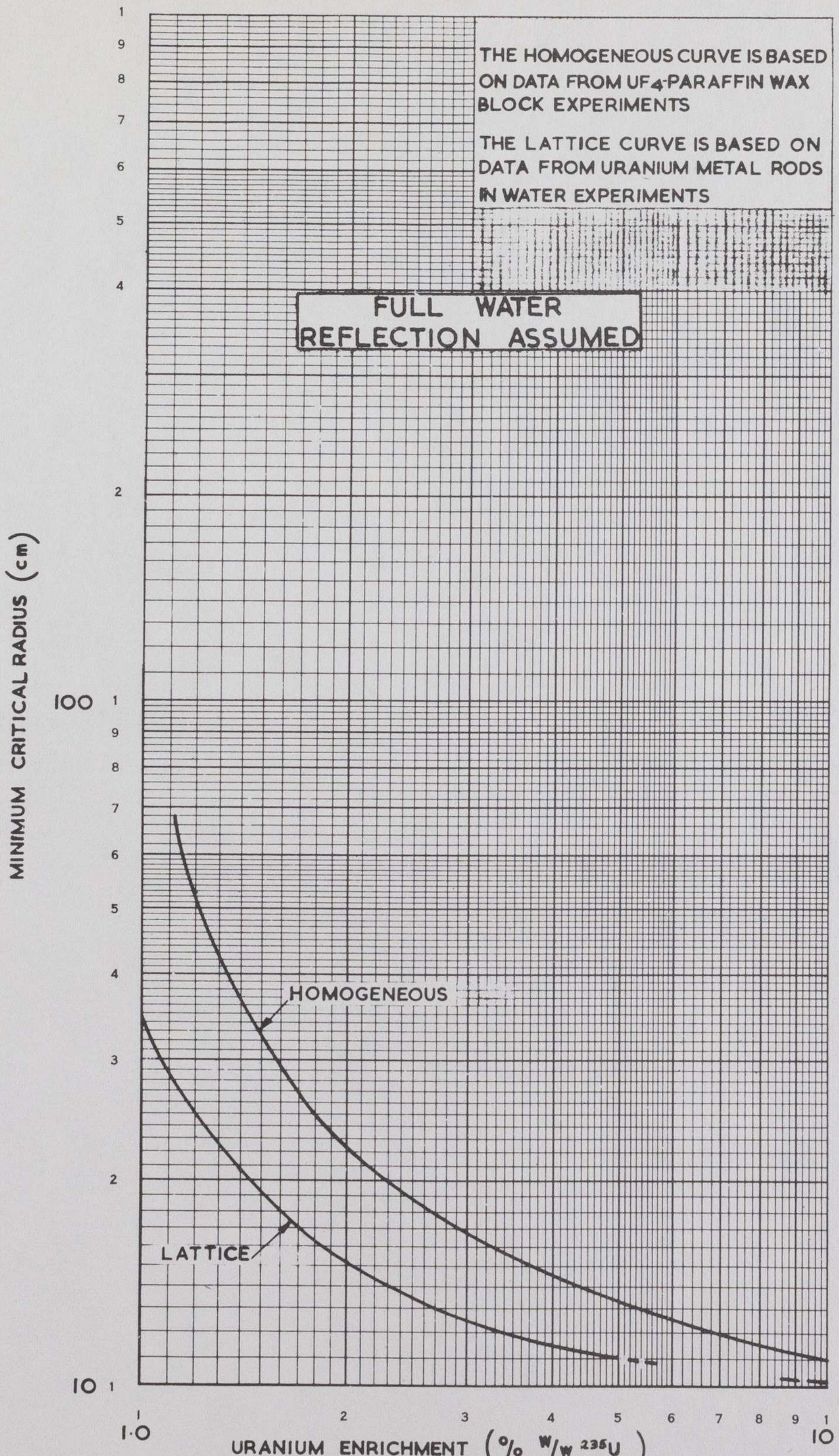

FIG. E3 MINIMUM CRITICAL RADIUS OF INFINITE CYLINDER AGAINST ENRICHMENT FOR LESS THAN 5 % $^{W}/_{W}$ ^{235}U

Note on the use of Fig. E4. Minimum critical slab thickness curve

The maximum safe slab thickness is three-quarters of the minimum slab thickness for the appropriate type of system.

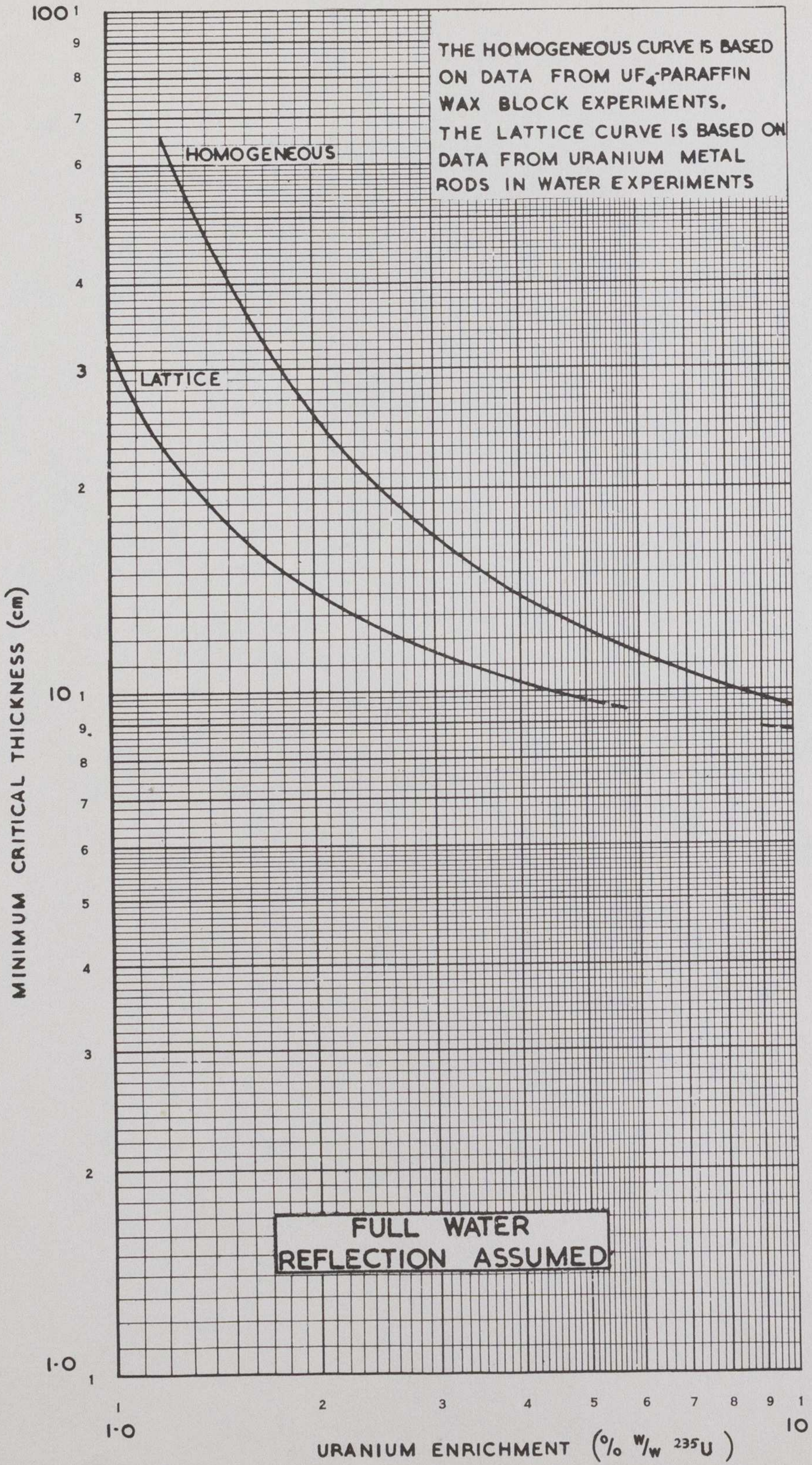

FIG. E4 MINIMUM CRITICAL THICKNESS OF INFINITE SLAB AGAINST ENRICHMENT FOR LESS THAN 5 % w/w ^{235}U

NOTES ON THE USE OF FIGS E5-8

Critical parameter curves less than 5% ^{235}U

(i) The curves can be used for homogeneous and randomly heterogeneous solutions and mixtures as defined in paragraph 4 (page E1).

(ii) Spot values are given of the H/U ratio at certain uranium concentrations. The continuous variation of this ratio with concentration is shown in Fig. C5. Also indicated are the following two approximate physical regions:

(a) Concentrated solutions up to the solubility limit of 1-1·2 g/cm^3

(b) Mixtures having uranium concentrations not exceeding those of homogeneous UF_4-paraffin wax mixtures below H/U = 20.

(iii) The curves refer to a single fully water-reflected vessel free from neutron interaction.

(iv) The broken sections of the curves are given as an indication of their trends only and are not to be used for safety assessments.

Notes on the use of Fig. E5. Critical mass curves

(1) In the concentration ranges covered by the solid parts of the curves the maximum safe mass of uranium is three-quarters of the critical mass for the worst credible conditions.

(2) If the uranium concentration can be guaranteed to remain either below the lower limiting critical concentration or above the upper limiting critical concentration no critical condition can arise.

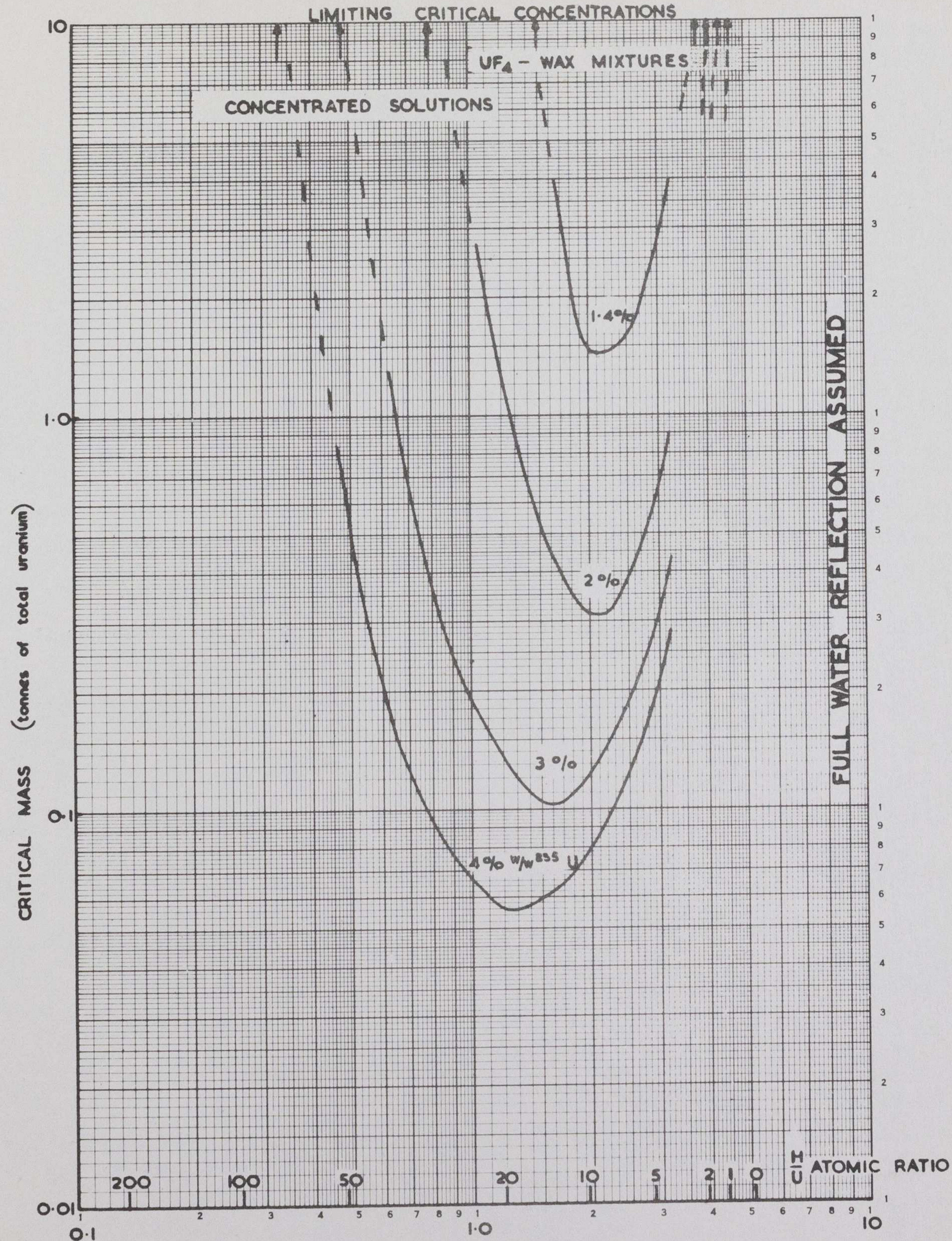

FIG E5. CRITICAL MASS AGAINST URANIUM CONCENTRATION FOR 1·4, 2, 3, 4% w/w 235U

Note on the use of Fig. E6. Critical volume curves

In the concentration ranges covered by the solid parts of the curves the maximum safe volume is three-quarters of the critical volume for the worst credible conditions.

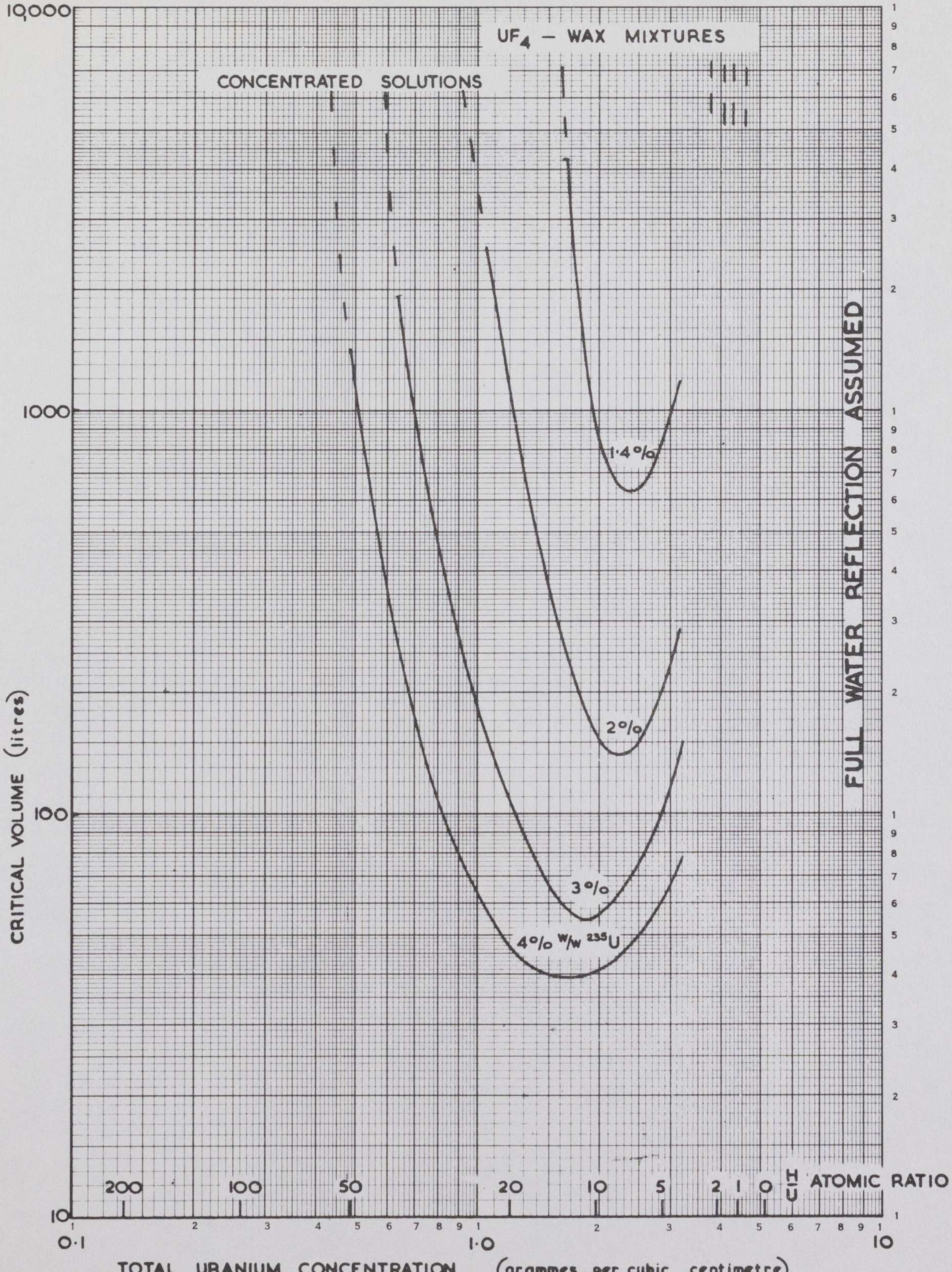

FIG E6. CRITICAL VOLUME AGAINST URANIUM CONCENTRATION FOR 1·4, 2, 3, 4 % w/w ^{235}U

Note on the use of Fig. E7. Critical cylinder radius curves

In the concentration ranges covered by the solid parts of the curves the maximum safe cross-sectional area of a cylinder is three-quarters of the critical cross-sectional area for the worst credible conditions (i.e. the safe cylinder radius is 85% of the critical radius).

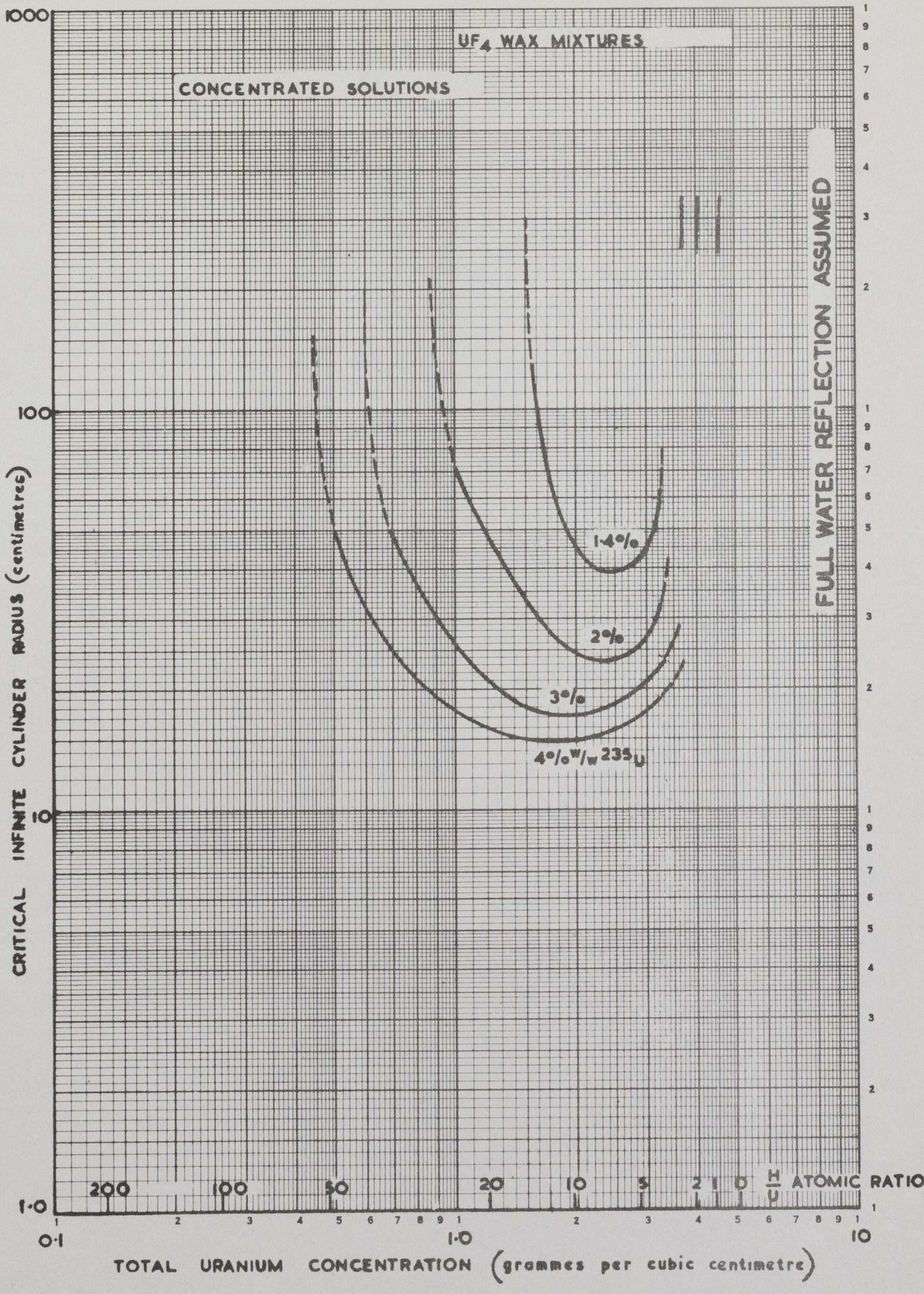

FIG. E7. CRITICAL INFINITE CYLINDER RADIUS AGAINST URANIUM CONCENTRATION FOR 1·4, 2, 3, 4 % w/w ^{235}U

Note on the use of Fig. E8. Critical slab thickness curves

In the concentration ranges covered by the solid parts of the curves the maximum safe slab thickness is three-quarters of the critical thickness for the worst credible conditions.

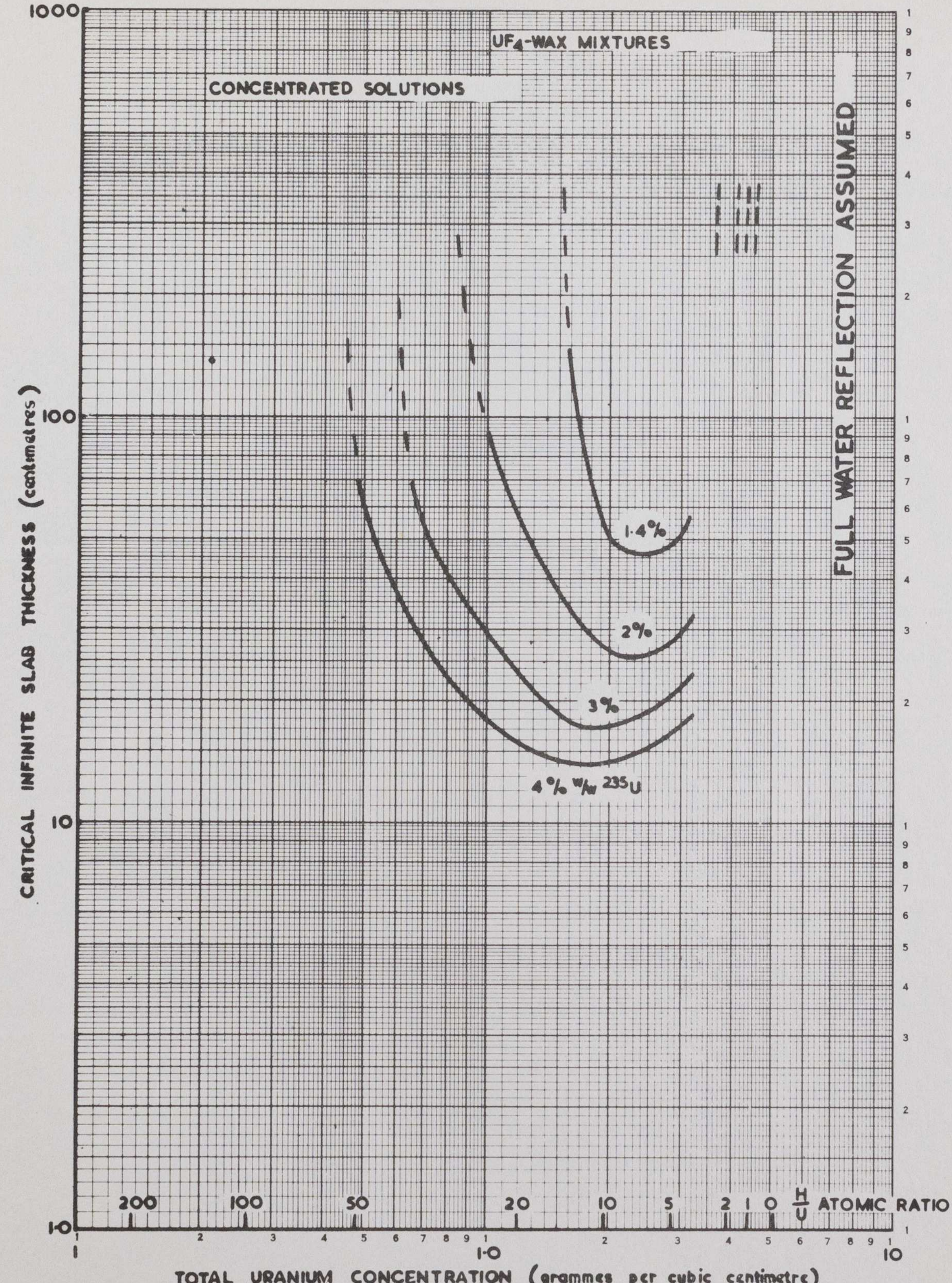

FIG. E8. CRITICAL INFINITE SLAB THICKNESS AGAINST URANIUM CONCENTRATION FOR 1·4, 2, 3, 4% w/w ^{235}U

SECTION F: Criticality data for uranium fluoride systems

1. In certain processes the compound often giving the maximum uranium concentration for a given H/U atomic ratio is uranyl fluoride (UO_2F_2). The uranium concentrations obtainable with various fluoride-water compounds and mixtures at H/U atomic ratios less than 20:1 are significantly less than those obtainable with metal-water mixtures. The maximum credible uranium concentrations of fluoride-water compounds and mixtures for many processes (e.g. in the diffusion plant) are shown in Fig. F9 for H/U atomic ratios less than 20:1.* (These may be compared with the corresponding metal-water figures in Fig. C5). For higher H/U atomic ratios the concentration of uranium in fluoride-water and metal-water mixtures are assumed to be the same for safety assessment purposes. The uranium concentration of anhydrous uranyl fluoride is taken as 5·1 g/cm^3.

2. The critical mass of uranium fluoride-water systems is greater than that of a metal-water mixture for H/U atomic ratios less than 20:1 because of the reduced concentration of uranium for any given H/U ratio. This difference becomes greater as the H/U ratio decreases and is greatest at H/U ratio = 0. At uranium enrichments greater than 30% w/w ^{235}U the resulting effect is to raise the smallest critical volume at H/U = 0 significantly above the minimum volume found in the solution range of metal-water systems. Hence, in fluoride-water systems of all enrichments there is a clearly defined minimum critical volume, occurring in the solution range at high enrichments and tending toward lower H/U atomic ratios as enrichment decreases. There are also clearly defined minimum values for mass, cylinder radius and slab thickness. For enrichments above 5% w/w ^{235}U the minima for fluoride systems are almost identical with the solution minima shown in sections C and D. Graphs of minimum fluoride parameters against enrichment are given in Figs F1-4. For enrichments below 5% w/w ^{235}U the minimum volumes, etc. occur at H/U atomic ratio less than 20:1.

3. The uranium concentrations shown in Fig. F9 are greater than those for the UF_4-paraffin wax mixtures at the same H/U ratio shown in Fig. C5. Hence, in this region, the critical mass of uranium fluoride-water systems is less than that given in section E. The minimum parameters for fluoride systems are given in Figs F1-4 and have been derived from the data of section E allowing for the increase in uranium concentration. Curves are also given of the variation of critical mass, etc. with uranium concentration at enrichments of 1·4%, 2·0%, 3·0% and 4·0% w/w ^{235}U (Figs F5-8). These were also derived from the corresponding ones in section E. At higher enrichments the curves of sections C and D can be used for fluoride-water systems.

4. For the convenience of plant operators a further graph (Fig. F10) has been added, showing the variation of mass of hydrogen (as obtained from H_2O, HF, etc. content) with mass of total uranium. The curves at the various ^{235}U enrichments are derived from Fig. F5. Some lines of constant H/U atomic ratio are also shown and, in particular, those lines that are asymptotic values for the curves of uranium - hydrogen mixtures at the given enrichments. If the H/U atomic ratios in any mixture can be guaranteed to remain above the upper asymptotic values of this ratio or below the lower asymptotic values no critical condition can arise.

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*REFERENCE: Notes of a meeting held at Capenhurst on 2nd May, 1960, to discuss maximum uranium concentrations occurring in the diffusion plant.

NOTES ON THE USE OF FIGS F1-4

Minimum critical parameter curves for uranium-fluoride systems

(i) The curves can be used for homogeneous and randomly heterogeneous solutions and mixtures as defined in paragraph 1 and Fig. F9.

(ii) The curves refer to a single fully water-reflected vessel free from neutron interaction.

(iii) The limiting critical enrichment is 1·0% w/w ^{235}U.

Note on the use of Fig. F1. Minimum critical mass curve

In the enrichment range covered by the solid part of the curve the maximum safe mass of uranium is three-quarters of the minimum critical mass.

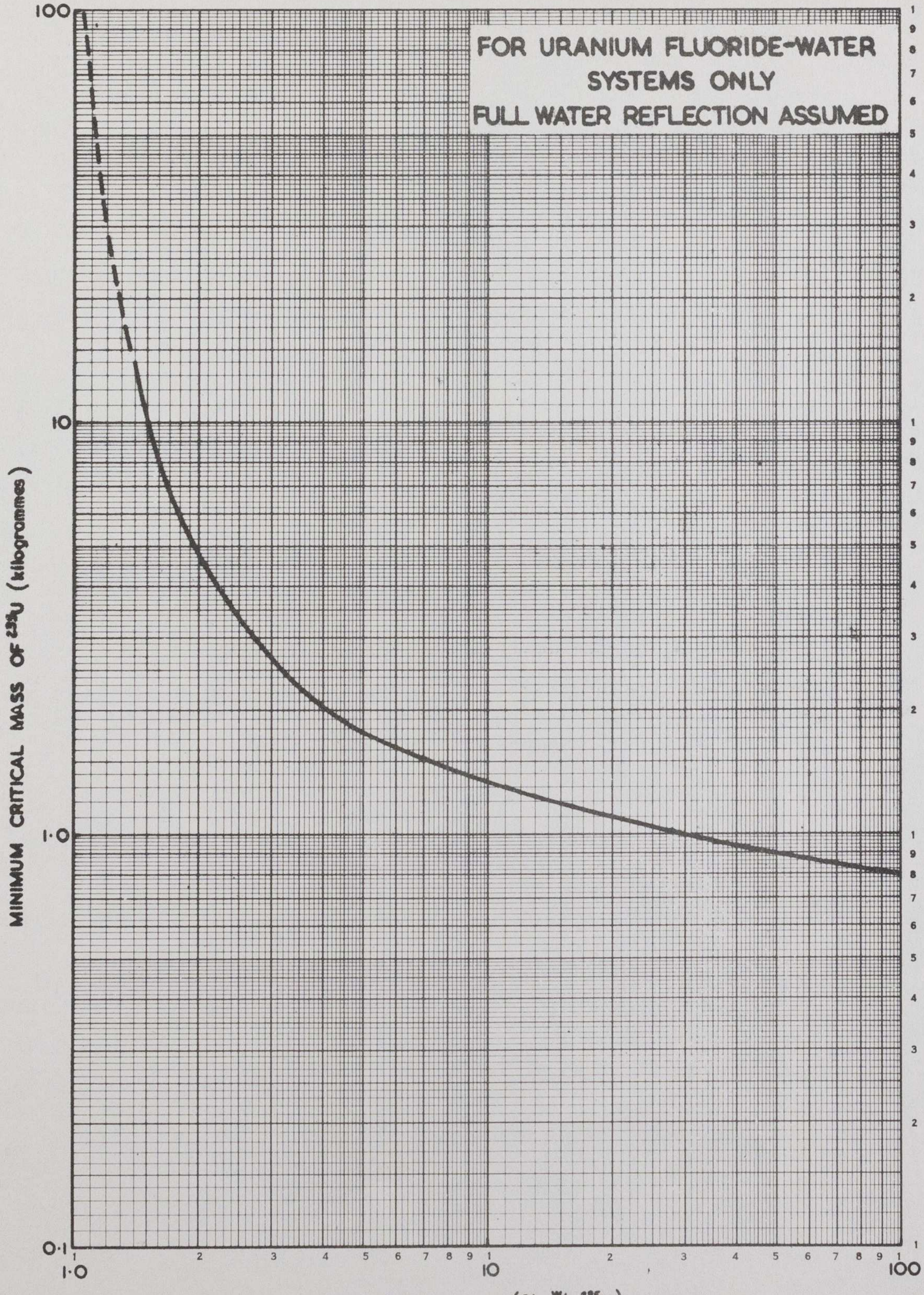

FIG. F1. MINIMUM CRITICAL MASS OF ^{235}U AGAINST ENRICHMENT

Note on the use of Fig. F2. Minimum critical volume curve

In the enrichment range covered by the solid part of the curve the maximum safe volume is three-quarters of the minimum critical volume.

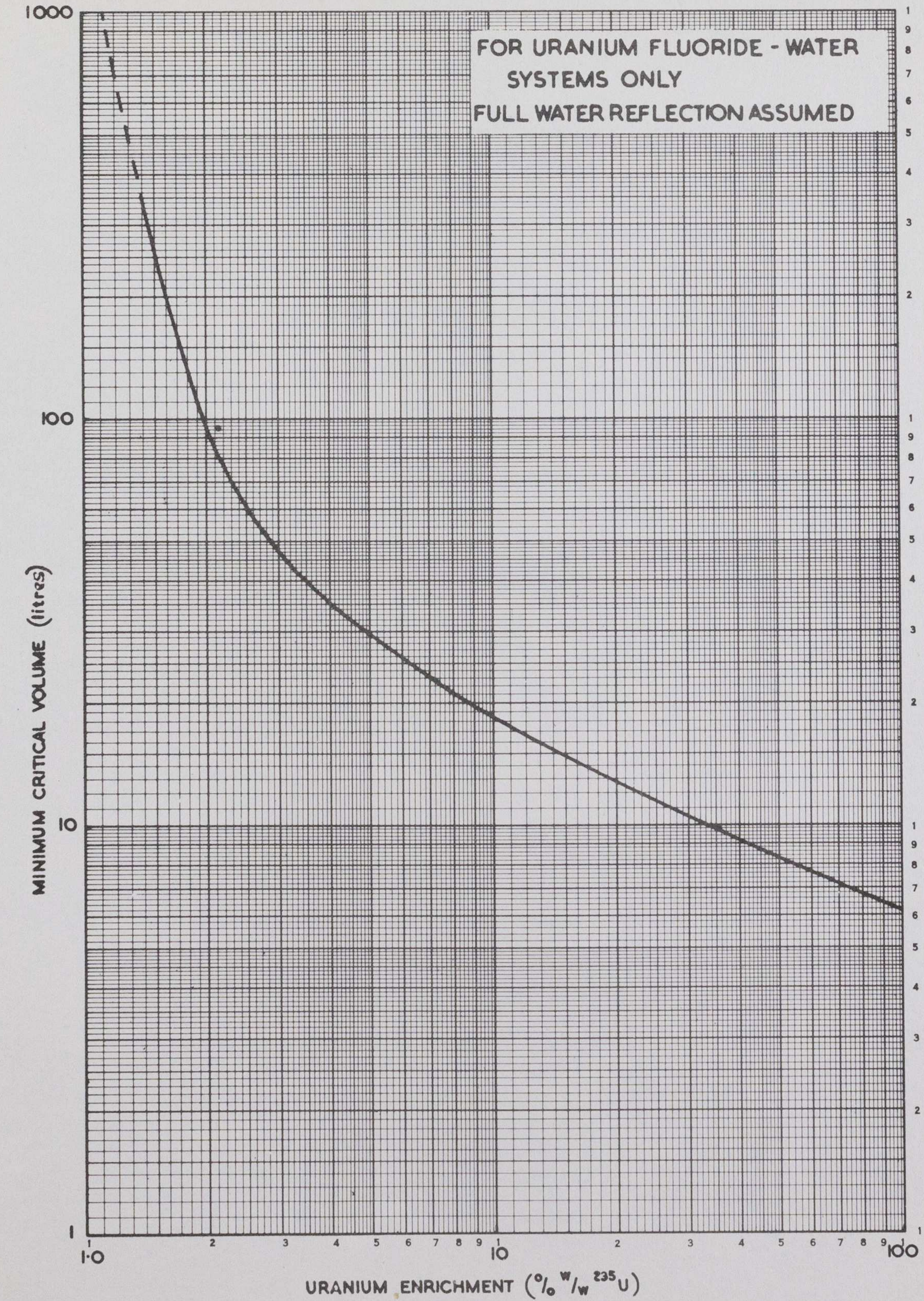

FIG. F2. MINIMUM CRITICAL VOLUME AGAINST ENRICHMENT

Note on the use of Fig. F3. Minimum critical cylinder radius curve

In the enrichment range covered by the solid part of the curve the maximum safe cross-sectional area of a cylinder is three-quarters of the minimum critical cross-sectional area (i.e. the safe cylinder radius is 85% of the critical one).

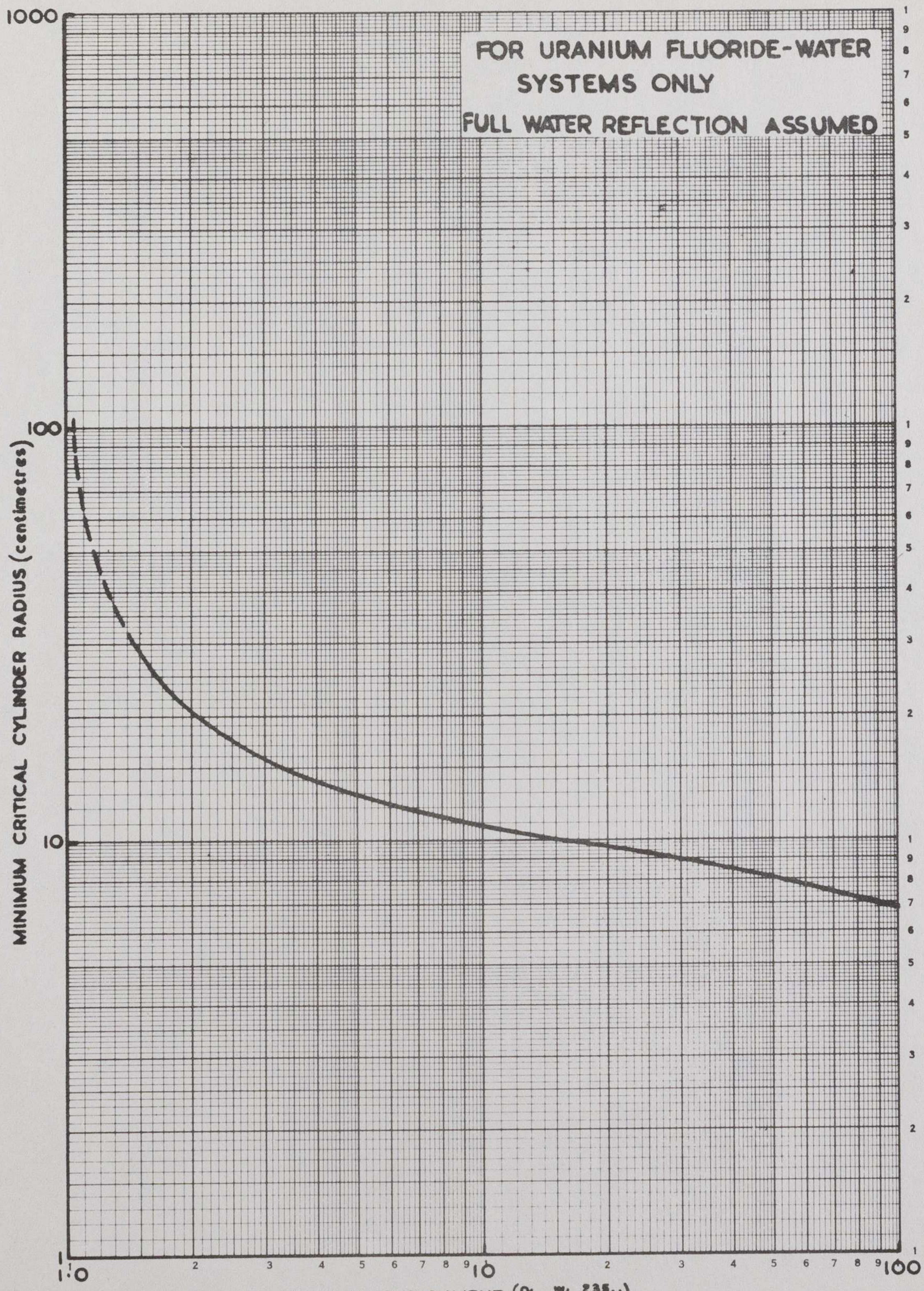

FIG F3 MINIMUM CRITICAL INFINITE CYLINDER RADIUS AGAINST ENRICHMENT

Note on the use of Fig. F4. Minimum critical slab thickness curve

In the enrichment range covered by the solid part of the curve the maximum safe slab thickness is three-quarters of the minimum critical slab thickness.

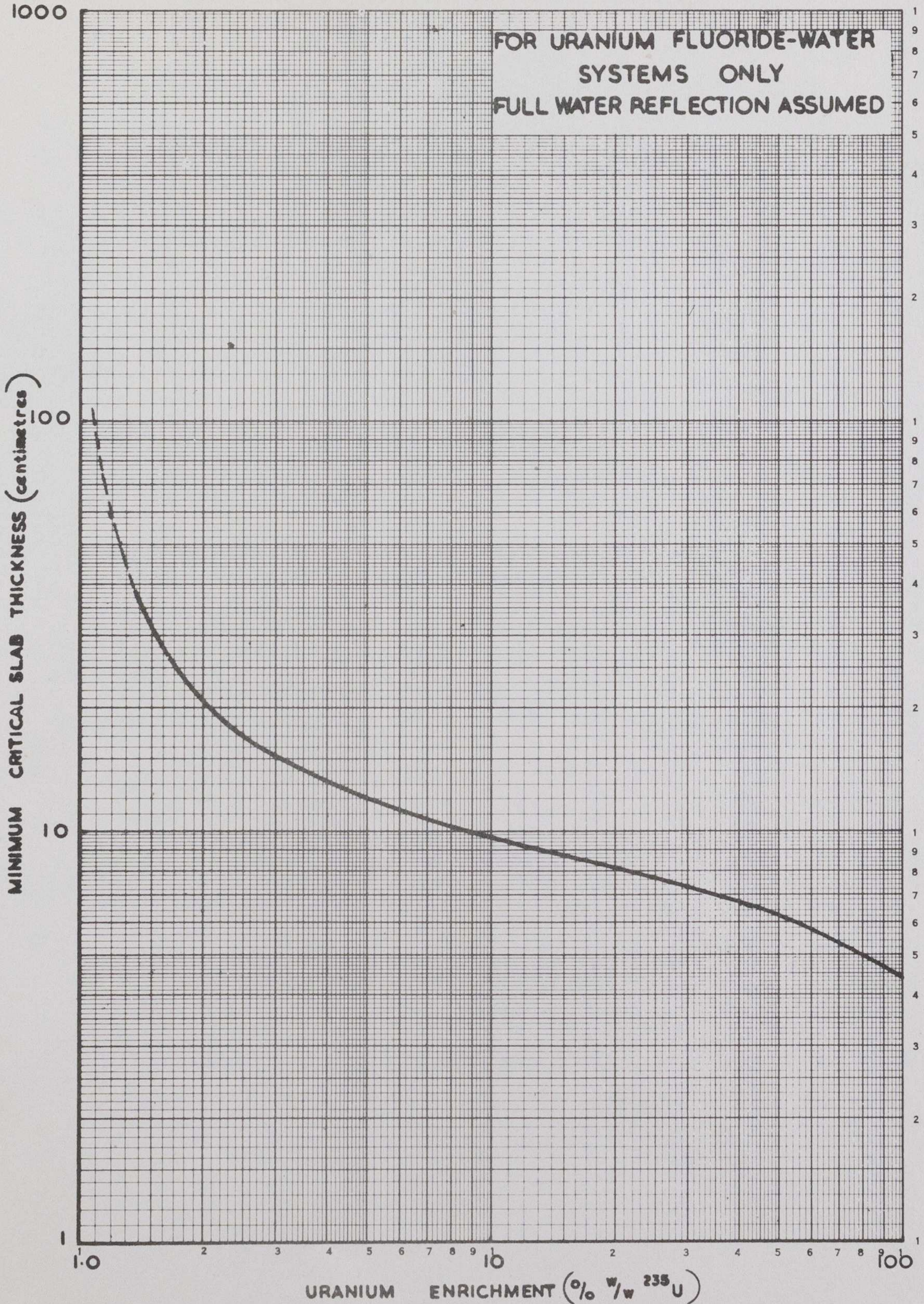

FIG.F4. MINIMUM CRITICAL INFINITE SLAB THICKNESS AGAINST ENRICHMENT

NOTES ON THE USE OF FIGS F5-8

Critical parameter curves for fluoride systems of less than 5% ^{235}U enrichment

(i) The curves can be used for homogeneous and randomly heterogeneous solutions and mixtures as defined in paragraph 1 and Fig. F9.

(ii) Spot values are given of the H/U ratio at certain uranium concentrations. The continuous variation of this ratio with concentration is shown in Fig. F9 for H/U $\leqslant$ 20 and in Fig. C5 for H/U $>$ 20. Also indicated are the following two approximate physical regions:

(a) Concentrated solutions up to the solubility limit of 1-1·2 g/cm^3.

(b) Mixtures having uranium concentrations not exceeding those of Fig. F9 for H/U $<$ 20.

(iii) The curves refer to a single fully water-reflected vessel free from neutron interaction.

(iv) The broken sections of the curves are given as an indication of their trend only and are not to be used for safety assessments.

Notes on the use of Fig. F5. Critical mass curves

(1) In the concentration ranges covered by the solid parts of the curves the maximum safe mass of uranium is three-quarters of the critical mass for the worst credible conditions.

(2) If the uranium concentration can be guaranteed to remain either below the lower limiting critical concentration or above the upper limiting critical concentration, no critical condition can arise.

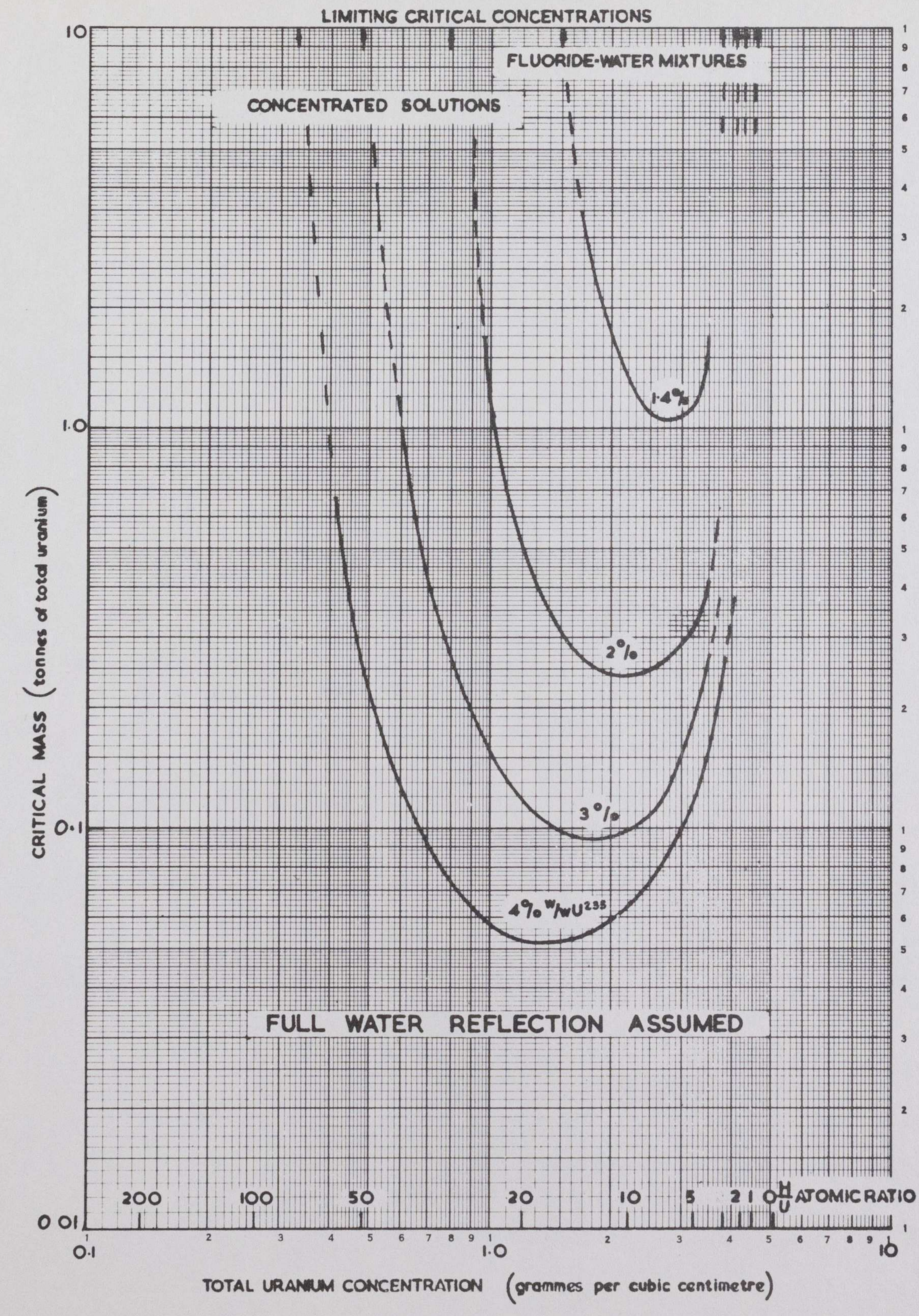

FIG. F5. CRITICAL MASS AGAINST URANIUM CONCENTRATION FOR 1·4, 2, 3, 4 % $^{w}/_{w}$ ^{235}U

Note on the use of Fig. F6. Critical volume curves

In the concentration ranges covered by the solid parts of the curves the maximum safe volume is three-quarters of the critical volume for the worst credible conditions.

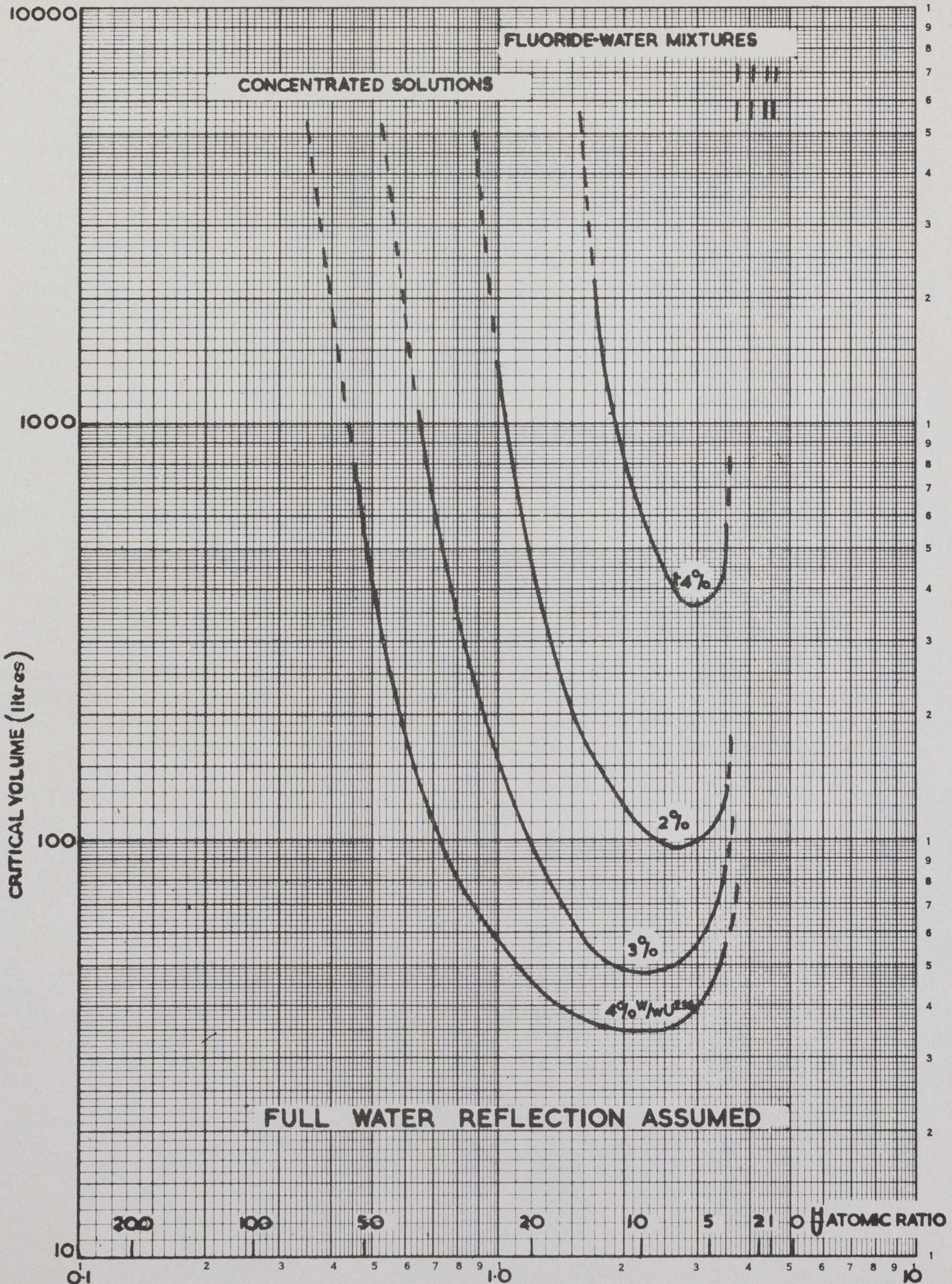

FIG. F6. CRITICAL VOLUME AGAINST URANIUM CONCENTRATION FOR 1·4, 2, 3, 4 % W/W ^{235}U

Note on the use of Fig. F7. Critical infinite cylinder radius curves

In the concentration ranges covered by the solid parts of the curves the maximum safe cross-sectional area of a cylinder is three-quarters of the critical cross-sectional area for the worst credible conditions (i.e. the safe cylinder radius is 85% of the critical one).

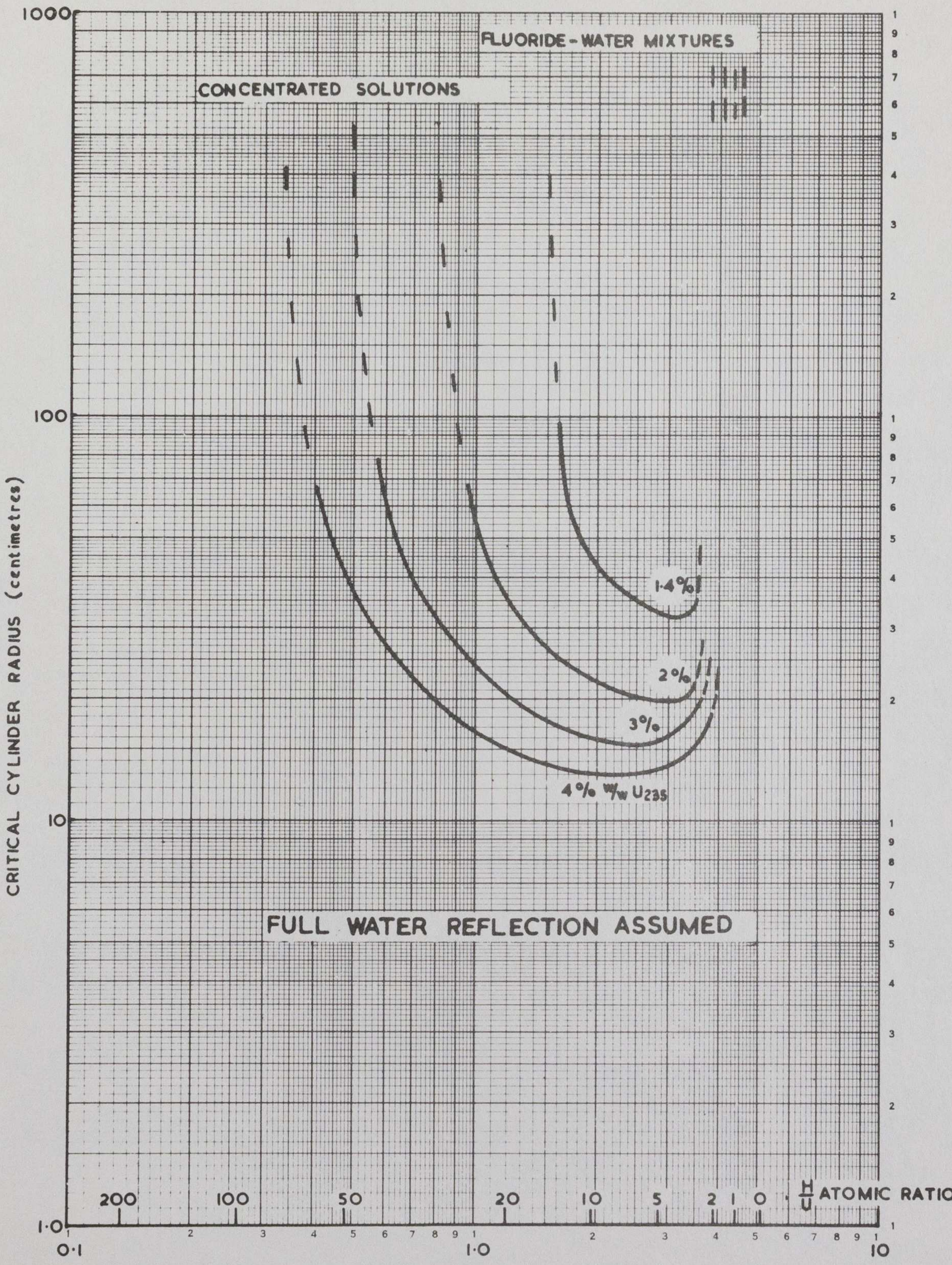

FIG. F 7. CRITICAL INFINITE CYLINDER RADIUS AGAINST URANIUM CONCENTRATION FOR 1·4, 2, 3, 4% w/w ^{235}U

Note on the use of Fig. F8. Critical infinite slab thickness curves

In the concentration ranges covered by the solid parts of the curves the maximum safe slab thickness is three-quarters of the critical slab thickness for the worst credible conditions.

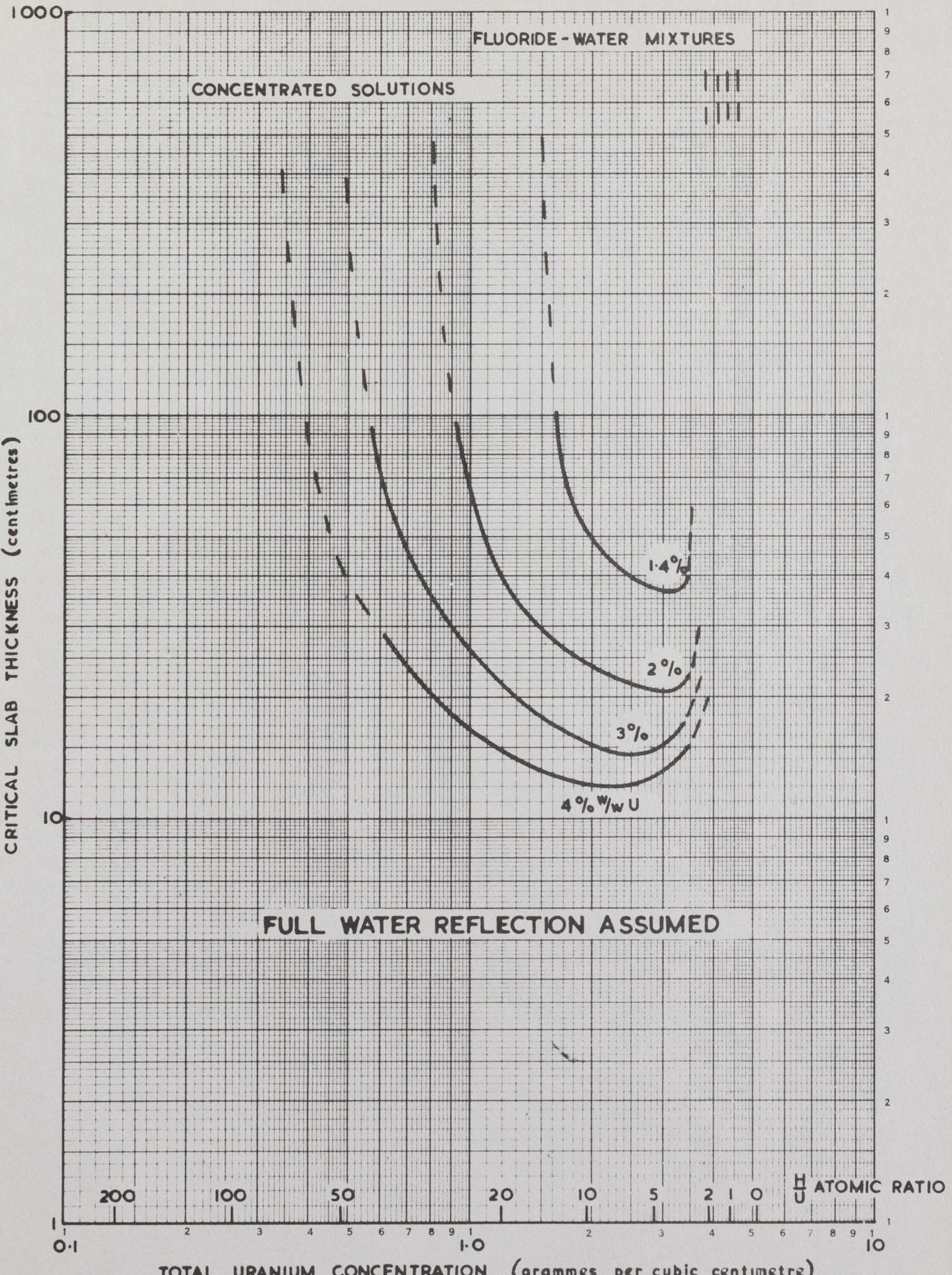

FIG. F8. CRITICAL INFINITE SLAB THICKNESS AGAINST URANIUM CONCENTRATION FOR 1·4, 2, 3, 4% w/w ^{235}U

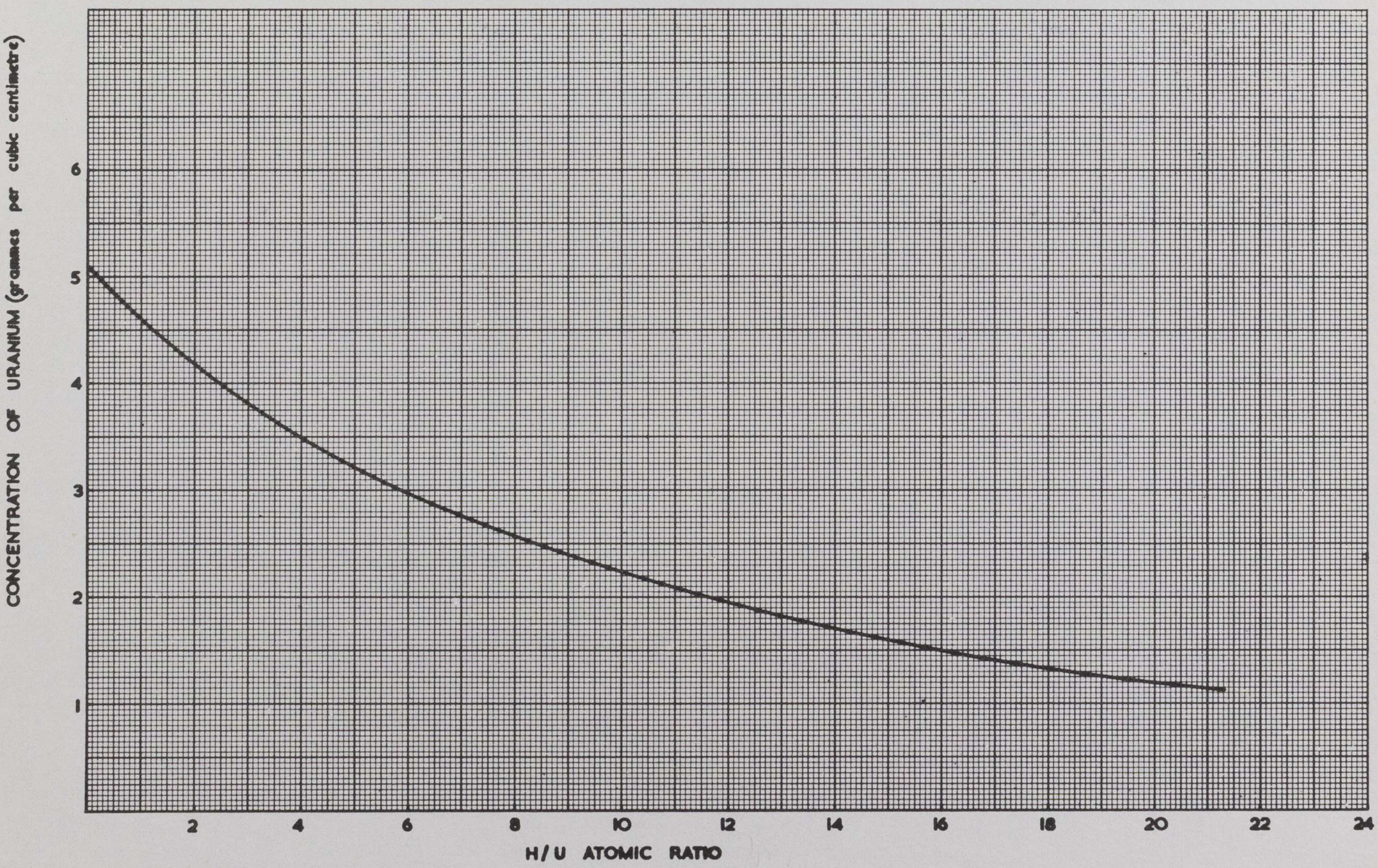

FIG. F9. URANIUM CONCENTRATION AGAINST H/U ATOMIC RATIO FOR URANIUM FLUORIDE-WATER MIXTURES

Notes on the use of Fig. F10. Hydrogen-uranium mass curves

(1) In the mass ranges covered by the solid parts of the curves the maximum safe hydrogen mass is three-quarters of the minimum mass for a critical assembly. Any mass of uranium may then be present.

(2) Similarly, in the mass ranges covered by the solid parts of the curves the maximum safe uranium mass is three-quarters of the minimum mass for a critical assembly. Any mass of hydrogen may then be present.

(3) The dotted sections of the curve are given only as an indication of trend and are not to be used in safety assessments.

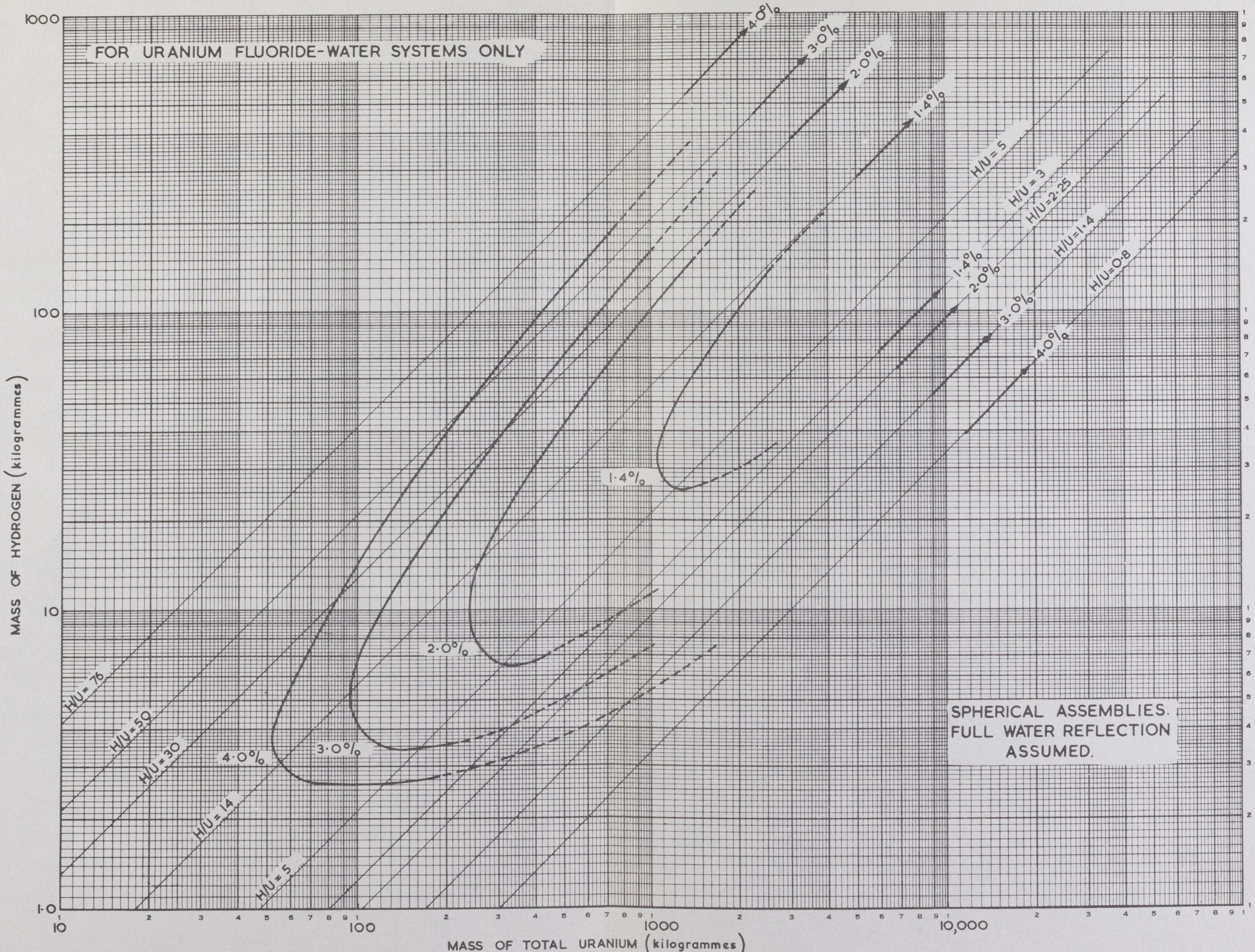

FIG. F. 10. CRITICAL MASS OF URANIUM – WITH – HYDROGEN IN URANIUM FLUORIDE-WATER MIXTURES OF ^{235}U ENRICHMENTS 1·4, 2·0, 3·0 AND 4·0% W/W

SECTION G: Criticality data for special systems

Subsequent additions to this handbook will include data on special systems not covered in sections B to F in which the moderator and/or reflector is graphite, beryllium and beryllium oxide. Other special systems to be considered are high-density compounds of uranium which for the same concentrations have higher H/U ratios (e.g. hydrides) than those given in sections B to F.

SECTION H: Rules for interacting systems

All the data presented in sections B to F are for a single fully-reflected vessel only. In this section the effect of neutron interaction between vessels is considered. For present purposes only a few general rules are presented, but in subsequent additions to this section a fuller treatment of this problem will be given.

These rules are intended to cover interaction between any number of vessels for which individual data are presented in sections B to F. They also allow for any conditions of reflection.

1. A plane array of identical spheres (or finite cylinders with height nearly equal to diameter) each having a volume of three-quarters of a single critical fully water-reflected sphere. The safe centre-to-centre pitch for this array is equal to 8 times the diameter of the sphere.

2. A single line of identical parallel long cylinders each having a cross-sectional area of three-quarters of a single critical fully water-reflected cylinder. The safe centre-to-centre pitch of this line is equal to 5 times the diameter of the cylinder.

3. An array of identical parallel large slabs each having a thickness of three-quarters of a single critical fully water-reflected slab. In this case, because the solid angle for interaction is so large, a rule analogous to rules 1 and 2 cannot be formulated. Instead, the array can be made safe by having at least 8 in. of Jabroc (density not less than 1·3 g/cm^3) between each pair of slabs together with a sheet of cadmium on each face of each slab. (The cadmium must be at least 0·025 in. thick and can be sprayed on to the slab tank surface). If a lower density wood is used, the thickness required is correspondingly increased, e.g. if beech (density not less than 0·6 g/cm^3) is used the thickness required is at least 12 in.

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